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J. S.

57

PROJECT SKYFIRE

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PROJECT SKYFIRE

by

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Forest Service
United States Department of Agriculture
Intermountain Forest and Range Experiment Station

November 1957

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I. OBJECTIVES

Project Skyfire is a program of basic research on lightning-caused forest fires. The project has two broad objectives: first, to gain basic information on the occurrence, behavior, and control of lightning-caused forest fires and on the characteristics of storms that produce these fires; and second, to develop methods for suppression of lightning fires, including study of cloud modification as a possible means of preventing or reducing the severity of lightning fires.

II. THE LIGHTNING FIRE PROBLEM IN AMERICAN FORESTS

Fire-setting lightning storms are a major source of damage to American forests. About 7500 lightning-caused forest fires occur annually in the United States. These fires cause severe damage to commercial timber and to the watershed, wildlife, and recreation values of forests. Wildfires spreading from lightning strikes often threaten human lives and property. The annual cost of lightning fires is more than 25 million dollars.

In the western United States, lightning is the greatest single cause of forest fires. Both the Rocky Mountain and Pacific Coast states have critical lightning fire problems (see table 1). In the Rocky Mountain states 70 percent of the forest fires are lightning-caused. During the 1956 fire season nearly 9500 lightning fires occurred in the 12 western states. Alaska also suffers from lightning fires: in 1957 more than 5 million acres were burned by lightning fires in the interior of Alaska.

In western forests lightning fires occur in every month from April through October. The peak lightning fire load normally comes in July and August, with occasional high occurrence in September. A critical feature of this problem is the occurrence of great numbers of fires within a few hours. In the northern Rockies more than 400 lightning fires have been started in a single 24-hour period. Such an outbreak of fires places a severe overload on fire suppression organizations and often results in some fires escaping early control and burning large forest areas. The most severe lightning fire conditions occur when an intense dry storm or a series of storms is preceded by a long period of drought and then is followed by dry and windy weather.

Lightning fire occurrence is greatest in the high mountain country of the Rockies and Pacific Coast and the high plateau forests of the Southwest. Studies made in the northern Rockies

Table 1.--Lightning fire occurrence in Rocky Mountain and Pacific Coast forests

State	Total no. of lightning fires, 1940-56	Average annual no. of fires	Percent of all fires caused by lightning
Rocky Mtn.			
Arizona	21,870	1,286	84%
Colorado	2,642	155	36
Idaho	16,953	997	69
Montana	10,414	613	72
Nevada	490	29	34
New Mexico	8,930	525	79
South Dakota	1,826	107	62
Utah	1,471	87	35
Wyoming	1,714	101	63
Total	66,310	3,900	70
Pacific Coast			
California	16,790	988	27
Oregon	17,173	1,010	53
Washington	8,631	508	28
Total	42,594	2,506	34
Grand totals, Western states	108,904	6,406	50

show that more than 400 fires per million acres may occur in elevation zones 7000 feet above sea level. (1). Fire fighting is difficult in this high mountain country. The rugged terrain and absence of roads hamper fire fighting and restrict the use of powered equipment for fire suppression.

The surest method for reducing damage from forest fires is fire prevention. In dealing with the lightning fire problem any method of reducing fire occurrence might have great economic importance. Of special importance would be a method for reducing the great peak loads of lightning fires that may be started by a single storm. For these reasons Project Skyfire is carrying on a comprehensive program of research in cloud seeding. If cloud seeding could reduce the severity of fire-setting lightning storms, a valuable new method for fire suppression would be available for protection of forests.

III. RESEARCH PROGRAM

Organization of Research Program

From the beginning of the Project Skyfire research program, a major part of the program has been to investigate the possibility of lightning suppression through cloud seeding. (14). However, analysis of this problem indicated that much basic information was needed before experiments in cloud seeding could be designed or the results understood. (2). Accordingly, the research program has been organized to include two major activities: first, gaining basic information on meteorological

variables, lightning storms, and lightning fires; and second, an experimental program in cloud modification.

Preliminary working plans for Project Skyfire indicated that research in these two major fields would require many specialized talents and a wide variety of scientific facilities. This is clearly a type of research endeavor calling for the pooling of resources and cooperation between several agencies. Initial research began as a joint effort by the Intermountain Forest and Range Experiment Station and The Munitalp Foundation, Inc. As the program grew, several other private, state, and federal agencies contributed manpower, facilities, and funds. Table 2 shows the general functions of each cooperating agency in the 1957 Project Skyfire research program.

Research Activities

The following is a summary of the principal Project Skyfire research activities.

Analysis of lightning fires.--Statistical studies have been made of lightning fires in the western United States. These studies show where lightning-caused fires are most prevalent, date and time of occurrence, speed of detection, rate of fire spread, area burned, and other data about lightning fire characteristics.

Cloud and lightning survey.--Since 1953 a network of lookout stations has been providing information on clouds and lightning storms in the northern Rocky Mountain area.

Table 2.--Functions of agencies participating in Project Skyfire research program

Agency	Function
U. S. Forest Service - Intermountain Forest and Range Experiment Station	General planning and supervision of research program; analysis of results; publication of reports; provision of research facilities.
U. S. Forest Service - National Forest Administration, Western Regions	Provision of personnel and facilities for cloud and lightning survey; communication facilities; aircraft operations.
The Munitalp Foundation, Inc.	General technical supervision, provision of scientific personnel and equipment.
U. S. Weather Bureau	Special weather forecasting; weather analysis; provision of special equipment.
Advisory Committee on Weather Control	Evaluation of results of cloud seeding experiments.
Meteorology Research, Inc.	Special studies of atmospheric nuclei and cloud physics; equipment development.
Montana State University	Special assistance in cloud and lightning survey; personnel training.
University of Washington	Development of mobile atmospheric laboratory; personnel training.
National Park Service	Assistance in cloud and lightning survey.
California State Division of Forestry	Assistance in equipment development; cooperation in analysis of cloud seeding results.

Cloud seeding review.--Studies have been made of the theory of cloud seeding and techniques for cloud modification. These studies have provided essential background information for the design of Project Skyfire's cloud seeding experiments.

Equipment development.--Specially developed equipment includes a mobile atmospheric laboratory, mobile radar unit, airborne cloud seeding generator, ground-based cloud seeding generator, wind tunnel for generator tests, cloud theodolite, and many special modifications of standard meteorological equipment.

Time-lapse photography.--Special time-lapse motion picture cameras have been used at numerous points to record the life cycle of clouds and thunderstorms.

Thunderstorm analysis.--Studies have been made of the origin, development, and intensity of thunderstorms in the northern Rocky Mountain area and of the associated atmospheric factors.

Cloud seeding experiments.--Field experiments in cloud seeding have included preliminary tests of techniques and equipment in northern Arizona, spring 1956; exploratory operations in the Lolo National Forest test area, Montana and Idaho, 1956; and a more extensive operation in the Lolo National Forest, 1957.

Atmospheric nuclei.--Studies have been made of the presence of freezing nuclei in Arizona and the northern Rockies. In connection with cloud seeding experiments studies have been made of the transportation, concentration, and deactivation of nuclei produced by cloud seeding generators.

Evaluation of cloud seeding results.--Detailed analysis of the results of Project Skyfire cloud seeding experiments is currently under way. This report summarizes results now known. Complete evaluation of the results to date must await completion of analyses now in progress.

IV. THEORETICAL CONSIDERATIONS FOR LIGHTNING SUPPRESSION

Thunderstorm Electrification

Many mechanisms have been proposed to describe the initial and large-scale charge separation in cumulus clouds leading to a lightning discharge. Those theories proposed prior to 1953 are summarized in various articles such as Chalmers (5), Gish (7), Gunn (8), and Wormell (19). More recent approaches are described by Gunn (9), (10), Wilson (18), and Vonnegut (17).

Except for the convective theory, the principle charge separation techniques proposed are based on the influence of falling rain, graupel, or hail. The falling hydrometeors carry with them a selected charge thus separating the charges of one sign from those left behind in the higher portion of the cloud. The initial charging of the hydrometeors may be due to one or a combination of the following processes: selective diffusion of ions of a certain sign to the hydrometeors; charging due to the breaking of liquid drops in an electric field; rubbing or fracturing of ice hydrometeors; and spacial redistribution of ions by updrafts and downdrafts in a cumulus cloud.

In some of the theories, a potential gradient or space charge is required either initially or to participate in a feedback or regenerative process. All the theories involve physical mechanisms which can be shown to produce charge separation in the laboratory. A basic problem in thunderstorm electricity is to show how the required initial charge separation

and large-scale charge accumulation can be produced in the atmosphere and still fit within the time and spacial boundaries of a thunderstorm.

The following meteorological processes appear to be most important in the theories mentioned:

1. All of the electrification theories require strong convective clouds and strong convective currents within the clouds.

2. All the theories require the existence of insulating air to permit the formation and persistence of intense electric fields.

3. Most of the theories require that the charge be separated by hydrometeors falling under the influence of gravity.

4. Many of the electrification theories are concerned with the coexistence of ice and supercooled water. Since the typical thunderstorm extends far above the freezing level and usually contains considerable ice, much emphasis has been placed on mechanisms for which ice is a necessary constituent for eventual lightning occurrence.

5. At least one theory is based on the effects of impurities in the water of hydrometeors. Experiments indicate that with this mechanism the amount and sign of the charge is a function of the type and concentration of the impurity.

6. The convection theory and the initiating mechanism of some of the other theories are related to the space charge being carried into the cloud by convection.

Thunderstorms and Cloud Seeding

Without trying to decide which theories are correct and which electrification mechanisms are probably most effective, a study of the various proposed mechanisms suggests how weather control can be used to decrease lightning and lightning-caused forest fires. The number and intensity of lightning strokes might be decreased by either altering the development of full-scale thunderstorms or by altering their electrical characteristics. The chances of preventing ignition and spread of some forest fires and help in suppression of existing fires would be realized if precipitation could be initiated or increased without increasing lightning. Cloud seeding for increasing rainfall will not be covered further except to note that experiments are being conducted by other projects to evaluate the possibility of increasing rainfall from summer convective clouds. There is as yet little evidence to show whether lightning would also be affected by seeding for rainfall increase.

A review of the electrification processes listed in the previous section suggests some interesting approaches to lightning suppression. In general, since strong convective currents are necessary to all of the electrification theories, if cloud seeding would inhibit the growth of such clouds or decrease the convective activity in existing active clouds, then some effect could be expected on the electrical development of the cloud. Other theories rely on the size, development, interaction and fall of both solid and liquid hydrometeors to separate charges

in the cloud. Therefore, the effect of cloud seeding on rate of growth, size, and distribution of these hydrometeors could change the electrification pattern in the cloud. Altering the conductivity of the air to reduce the accumulation of charge in certain areas or to conduct lightning to areas where the effect would be harmless has been the subject of many proposals. Metallic conductors and conducting smokes have been proposed to act as very tall lightning rods. Conceivably, the air could be ionized artificially, as by radioactivity, to alter the charge distribution. Processes involving ion convection might be altered by shielding with conductors or producing space charge by various types of ionization. Introduction of chemicals in a cloud may alter the amount and polarity of charges generated in the freezing process.

In summary, there is a variety of theories to account for the charging of clouds to produce lightning, and there is a variety of physical effects which can be expected from cloud seeding which may alter the build-up of charges. The large number of theories makes one optimistic that man can expect to affect lightning, but also points out the complexity of the problem and the need for basic research on cloud dynamics, hydrometeor growth, electrification, and the interrelationships between them. At the present time, with the information now available on the action of seeding agents on supercooled clouds, it appears that a direct approach can be made on lightning

suppression by inhibiting the build-up of cumulus clouds and by further altering the electrification of clouds by changing the distribution of supercooled particles.

Possible Methods for Lightning Suppression

As mentioned previously, although electrification mechanisms are still subject to various theories, it is universally agreed that most cloud-to-ground lightning strikes require large, convective type clouds (3), (4). Therefore, any seeding which would prevent such large clouds from forming should inhibit lightning, no matter what final electrification mechanisms actually cause lightning.

Assume that when precipitation begins in a cloud, decay of the cell starts setting in rapidly. If dry ice, silver iodide crystals, salt particles, or other conventional cloud seeding materials were to initiate precipitation earlier and at lower elevations than natural conditons, the cloud size could then presumably be kept smaller than usual. The lack of growth of one cloud can inhibit the subsequent growth of later clouds by preventing the raising of water vapor to cloud top altitudes. The assumption that precipitation helps to cause the decay of a cloud may be invalid in many cases.

Changing the size and intensity of a cumulus cloud by cloud seeding may have many direct effects on the electrical structure of the cloud. Since cloud dynamics, hydrometeor development, and electrical structure apparently are all interrelated in a complex fashion, it is difficult to separate them

for discussion. For example, seeding with the hope of inhibiting the overall cloud growth may alter the electrification process drastically because of the changes in the precipitation elements. A direct change in the electrical properties of the cloud may take place if sufficiently large numbers of active freezing nuclei can be introduced into the supercooled portion of a growing cloud. In this case, the liquid water would be shared among so many ice particles that none could grow large enough to fall faster than the updraft within the cloud. If all ice particles are carried to higher levels and no particles grow large enough to fall through the cloud, electrical charge separation would be less than if seeding had not occurred, and lightning would be less likely to occur. With elimination of rapid fall of hail or rain toward the ground, lightning strikes to ground might be reduced even more than cloud-to-cloud strikes.

There are many factors involved whereby precipitation may either inhibit or amplify cloud growth; determining just what may happen in a particular circumstance is beyond the capabilities of present theory and instrumentation. Precipitation can concentrate liquid water which in turn may weaken upcurrents. Precipitation evaporating below the cloud can cool the air through which it falls and likewise diminish the upcurrent. For long range effects, the seeding can cause glaciation of the cloud top and thus make a slowly evaporating shield which cuts off sunlight from the ground and inhibits further cumulus

development. Certain factors may be stimulated by cloud seeding to enhance the cloud development. Heat energy released when supercooled cloud particles evolve into ice can increase the instability in a cloud and accelerate growth. Glaciation at the cloud edges can inhibit evaporation and cloud decay. Increased precipitation may accelerate the transfer of charges in the cloud and initiate lightning at an earlier stage than it would naturally occur.

Immediate and long range reactions as a result of cloud seeding are complex. However, there is sufficient evidence to indicate that seeding may inhibit cloud growth and lightning occurrence.

V. CLOUD AND LIGHTNING SURVEY

Basic Cloud and Lightning Information

The Project Skyfire cloud seeding experiments require a considerable background of local weather and climatic data and a good understanding of cumulus clouds and lightning storms. Specific information needed includes: area and time distribution of lightning storms over target and surrounding areas; characteristics of individual lightning storms; location of cloud breeding areas; and location of consistent lightning storm paths. All of these factors influence the design and execution of experimental cloud seeding operations.

Network of Lookout Stations

A special network of 22 carefully selected fire lookout stations has been established in Montana, Idaho, northeastern Washington, eastern Oregon, and northwestern Wyoming (figure 1). The personnel at these stations make special observations of clouds and lightning. They are trained to perform both fire control and meteorological duties. A typical lookout station is shown in figure 2.

These observers record detailed data on clouds and lightning storms. These data include the location and time of formation of the first cumulus clouds and their development, movement, and rate of growth. The identification of middle and upper clouds, speed of their movement, surface temperature, relative humidity, and wind speed and direction are recorded at each station three times daily. Also, detailed charts and notes are prepared showing

Figure 1.--Location of 22 Skyfire lookout stations used in cloud and lightning survey over the northern Rockies in summer 1956 and 1957.

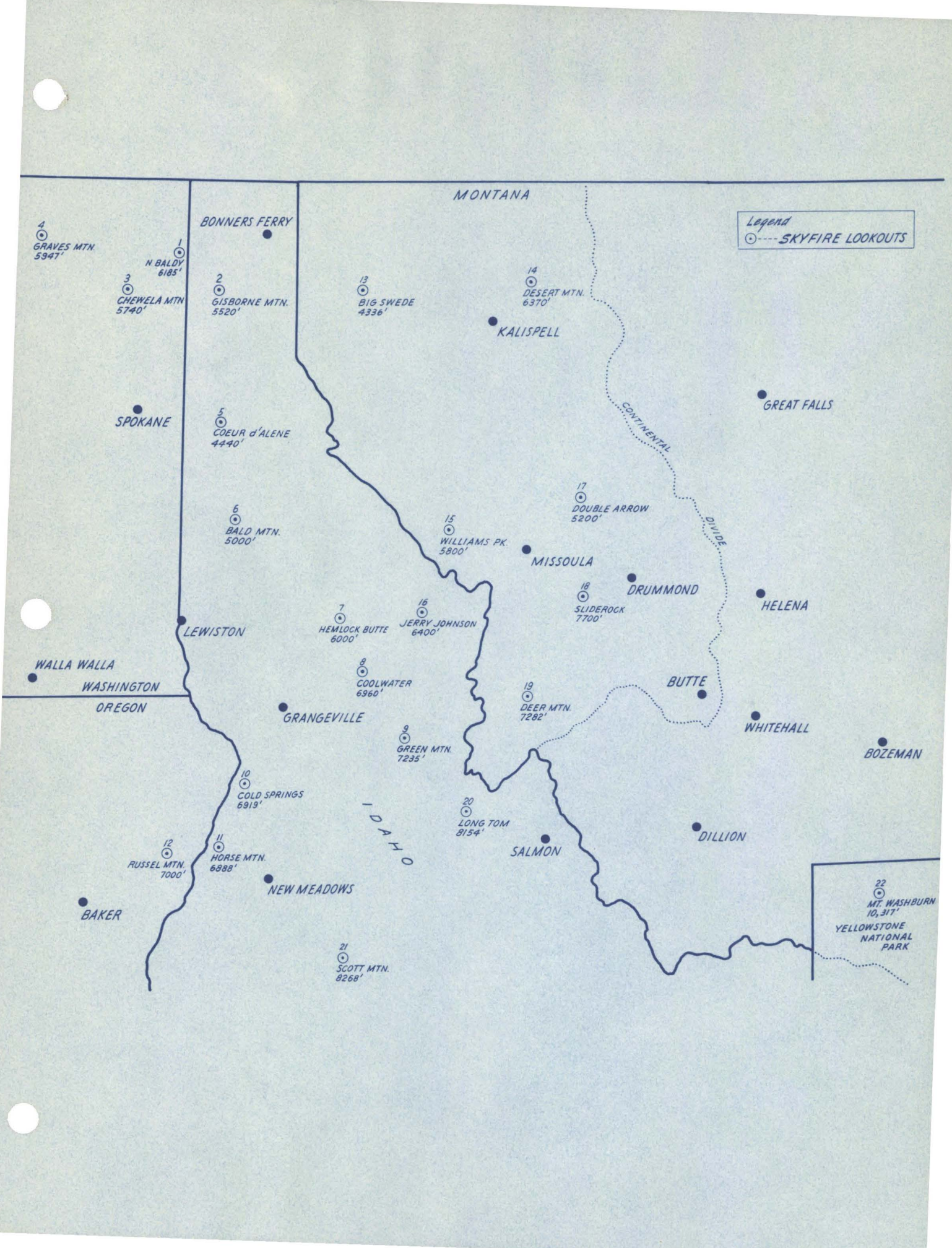

MONTANA
Legend
SKYFIRE LOOKOUTS
4
GRAVES MTN.
5947'
1
N. BALDY
6185'
3
CHEWELA MTN.
5740'
2
GISBORNE MTN.
5520'
13
BIG SWEDE
4336'
14
DESERT MTN.
6370'
BONNERS FERRY
KALISPELL
SPOKANE
5
COEUR d'ALENE
4440'
CONTINENTAL
DIVIDE
GREAT FALLS
17
DOUBLE ARROW
5200'
6
BALD MTN.
5000'
15
WILLIAMS PK.
5800'
MISSOULA
DRUMMOND
18
SLIDEROCK
7700'
HELENA
7
HEMLOCK BUTTE
6000'
16
JERRY JOHNSON
6400'
LEWISTON
WALLA WALLA
WASHINGTON
OREGON
8
COOLWATER
6960'
BUTTE
19
DEER MTN.
7282'
GRANGEVILLE
WHITEHALL
9
GREEN MTN.
7235'
BOZEMAN
10
COLD SPRINGS
6919'
20
LONG TOM
8154'
IDAHO
12
RUSSEL MTN.
7000'
11
HORSE MTN.
6888'
SALMON
DILLION
NEW MEADOWS
22
MT. WASHBURN
10,317'
YELLOWSTONE
NATIONAL
PARK
BAKER
21
SCOTT MTN.
8268'

Figure 2.--Gisborne Mtn. fire lookout, Kaniksu National Forest. A typical station in the Skyfire cloud and lightning survey network. Mountaintop lookout stations are ideal locations for collecting cloud and lightning data.

the origin, development, and movement of lightning storms and the actual number of lightning strikes associated with each storm.

A simplified cumulus coding system has been developed for reporting and mapping these cloud data (12). This code follows the dynamic growth cycle of cumulus clouds: (1) small fair weather cumulus, (2) towering cumulus, (3) cumulus clouds with glaciated tops, (4) cumulus clouds with virga, (5) cumulus clouds with precipitation reaching the ground, (6) the fully developed thunderstorm or cumulo-nimbus clouds.

In the cumulus observations, careful attention is given to determination of the cloud base, rate of growth of the cloud, and cloud movement. All these data are especially useful in the areas where lightning storms develop from the cumulus clouds in the immediate area.

Following is a typical cumulus situation over the network as shown in figures 3 and 4 for July 22, 1957. The 1200 and 1600 MST observations are shown. At 1200 MST, most of the stations report either fair weather or some towering cumulus clouds. However, some stations to the south and southwest are already reporting the more advanced stages of cumulus development including some cumulo-nimbus (or thunderstorm) clouds. At 1600 MST, the majority of the stations are reporting the fully developed thunderstorm stage.

Figure 5 shows the distribution and intensity of lightning storms on August 22. The area covered by storms at each station is outlined. The lightning storms on this date were associated with the passage of a cold front across the area, and the storm progression from SW to NE can be seen from the times indicated on the figure.

Results of Cloud and Lightning Survey

Operation of the Project Skyfire cloud and lightning survey network has shown the value of lookout stations for special weather observations. This system has demonstrated that forest fire lookout stations are in advantageous positions to gather and report essential information on clouds and lightning for use in cloud seeding research and general fire weather forecasting and analysis. The radio network linking fire lookout stations and forest fire dispatching centers to Project Skyfire headquarters provides a means for instant use of the data in cloud seeding operations.

Cloud breeding areas.--One objective of this program is to determine the location of areas in the northern Rockies that appear to be consistent cloud breeding sites. Survey experience during four observation seasons has revealed considerable variation in such sites. The principal mountain ranges are obviously sites that favor orographic cloud development. However, development of clouds near these ranges varies widely according to atmospheric factors. Day-to-day identification of specific cloud breeding sites requires study of topographic factors and both micro- and meso-scale analysis of atmospheric factors.

Figure 5.--Lightning map for July 22, 1957. Note general widespread development of thunderstorm situation and consistency in direction of storm movement.

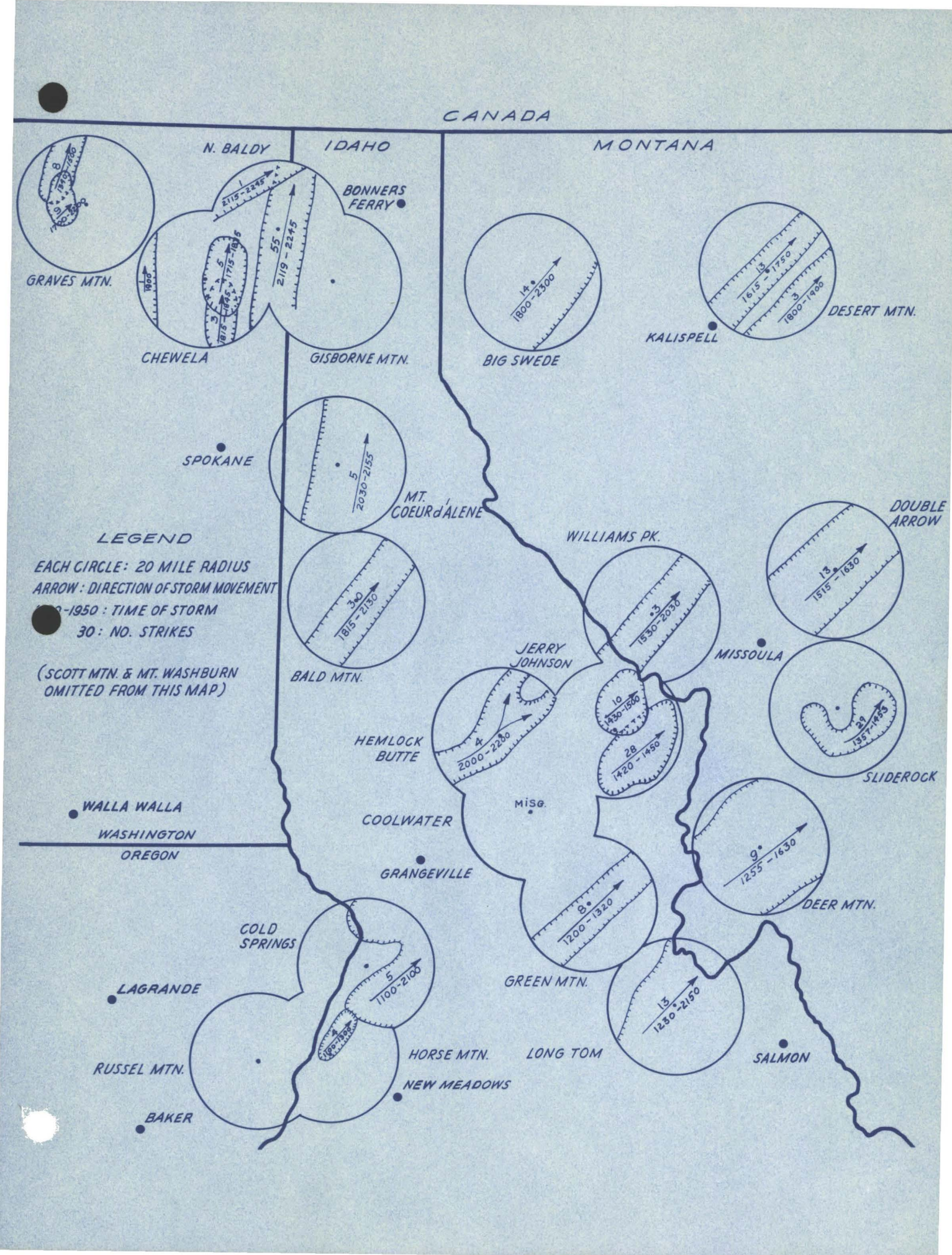

CANADA
IDAHO
MONTANA
N. BALDY
GRAVES MTN.
BONNERS FERRY
CHEWELA
GISBORNE MTN.
BIG SWEDE
KALISPELL
DESERT MTN.
SPOKANE
MT. COEUR d'ALENE
LEGEND
EACH CIRCLE: 20 MILE RADIUS
ARROW: DIRECTION OF STORM MOVEMENT
-1950: TIME OF STORM
30: NO. STRIKES
(SCOTT MTN. & MT. WASHBURN OMITTED FROM THIS MAP)
BALD MTN.
WILLIAMS PK.
DOUBLE ARROW
JERRY JOHNSON
MISSOULA
HEMLOCK BUTTE
SLIDEROCK
WALLA WALLA
WASHINGTON
OREGON
COOLWATER
GRANGEVILLE
COLD SPRINGS
LAGRANDE
DEER MTN.
GREEN MTN.
RUSSEL MTN.
HORSE MTN.
LONG TOM
SALMON
NEW MEADOWS
BAKER

Figure 3.--Cumulus cloud situation at 1200 hours, July 22, 1957.
Thunderstorms reported at 5 stations by Skyfire lookout network.

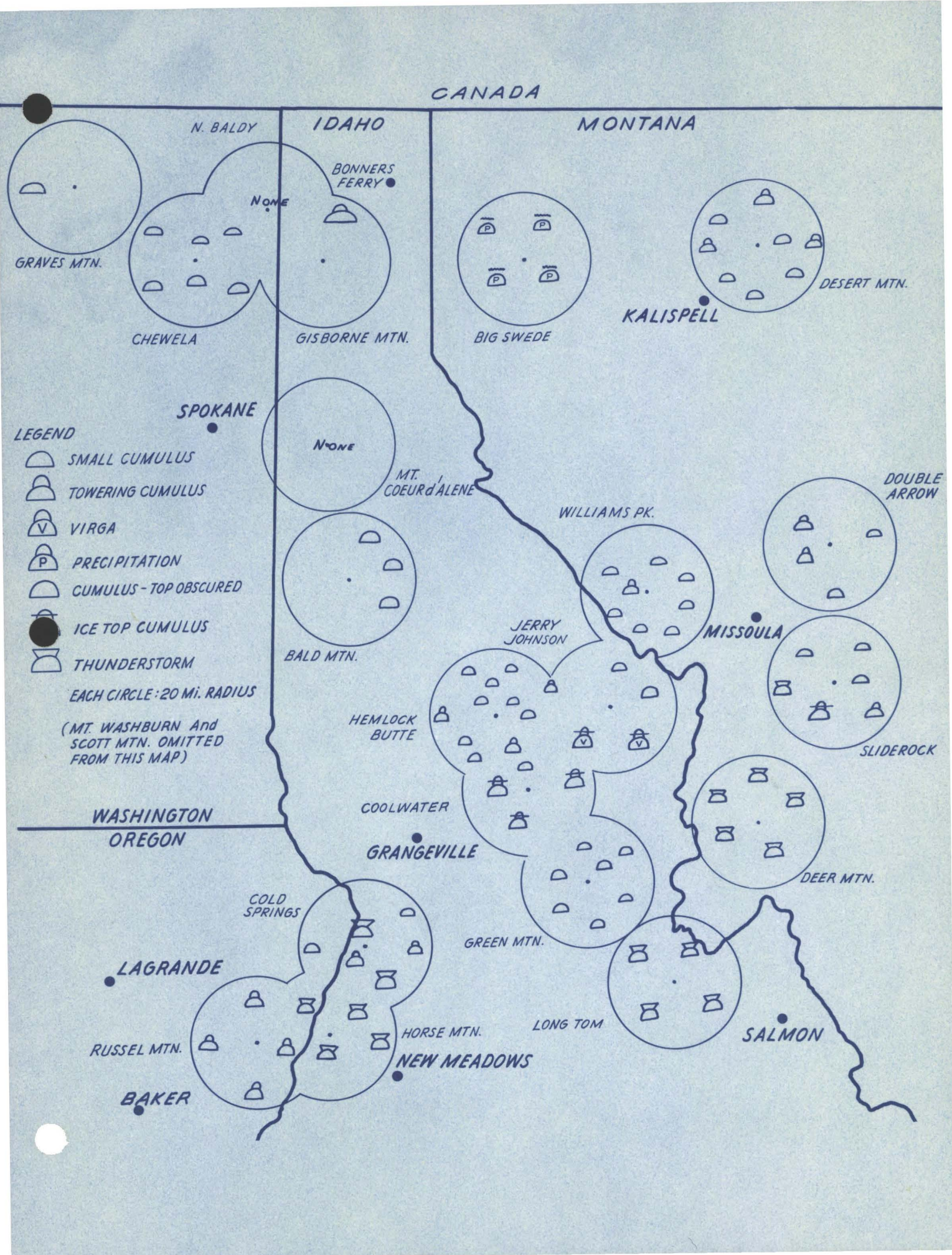
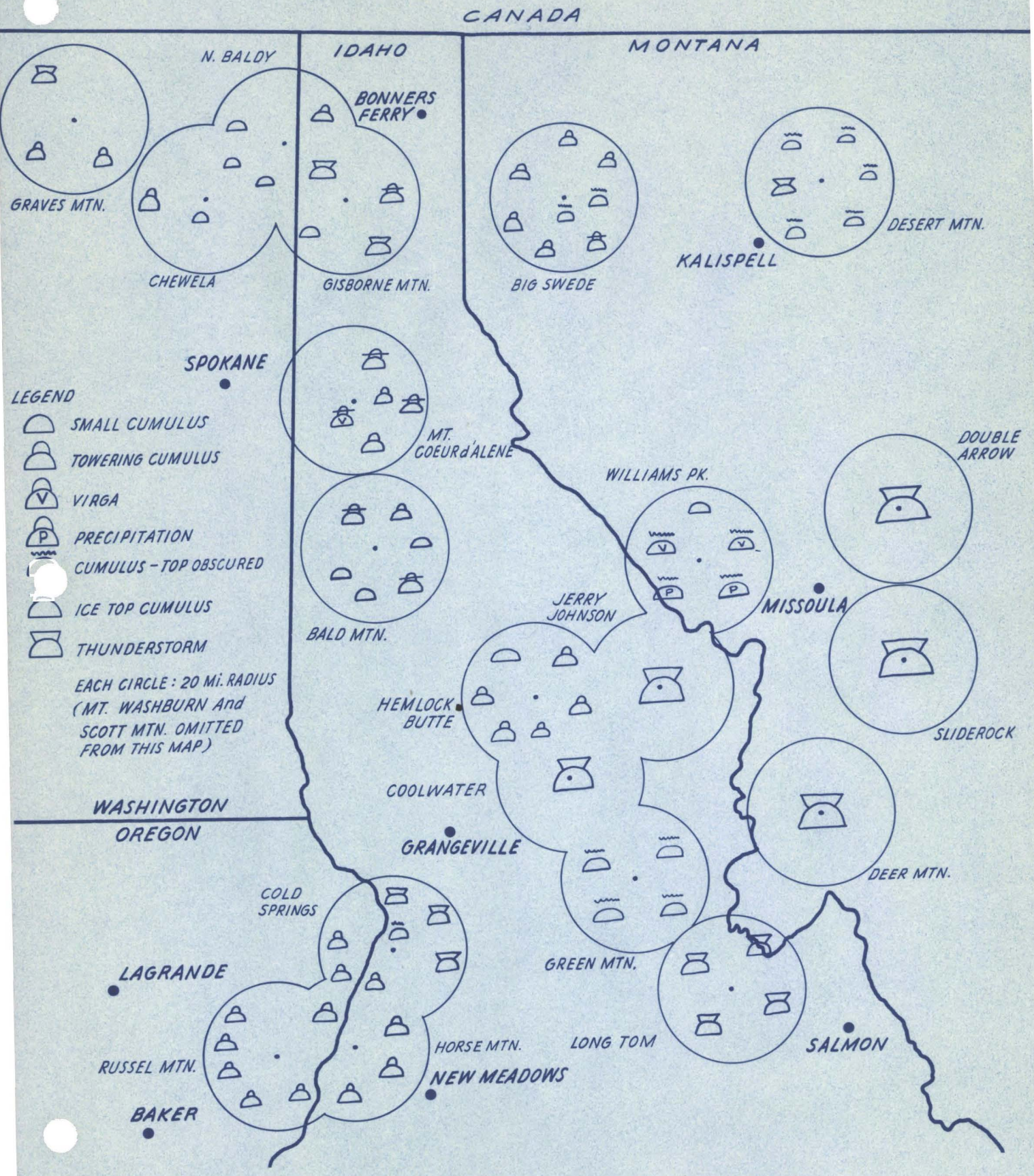

CANADA
IDAHO
MONTANA
N. BALDY
BONNERS FERRY
NONE
GRAVES MTN.
CHEWELA
GISBORNE MTN.
BIG SWEDE
KALISPELL
DESERT MTN.
SPOKANE
LEGEND
SMALL CUMULUS
TOWERING CUMULUS
VIRGA
PRECIPITATION
CUMULUS - TOP OBSCURED
ICE TOP CUMULUS
THUNDERSTORM
EACH CIRCLE: 20 Mi. RADIUS
(MT. WASHBURN And SCOTT MTN. OMITTED FROM THIS MAP)
NONE
MT. COEUR d'ALENE
BALD MTN.
WILLIAMS PK.
DOUBLE ARROW
JERRY JOHNSON
MISSOULA
HEMLOCK BUTTE
SLIDEROCK
WASHINGTON
OREGON
COOLWATER
GRANGEVILLE
DEER MTN.
COLD SPRINGS
GREEN MTN.
LAGRANDE
LONG TOM
SALMON
HORSE MTN.
RUSSEL MTN.
NEW MEADOWS
BAKER

Figure 4.--Cumulus cloud situation at 1600 hours, July 22, 1957. Thunderstorms reported at 10 of the 22 Skyfire stations indicated a substantial increase of lightning activity over the 1200-hour report.

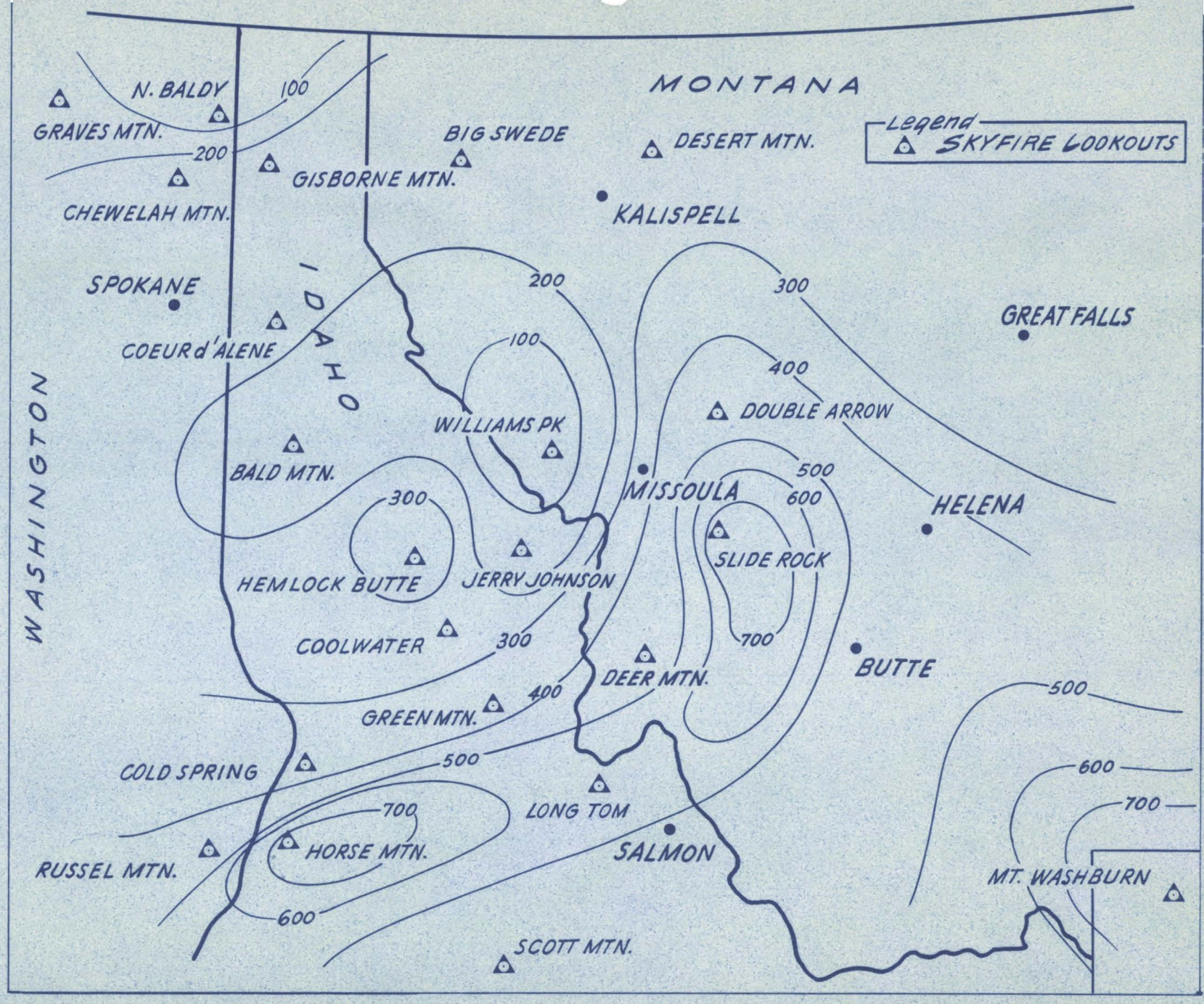

CANADA
IDAHO
MONTANA
N. BALDY
BONNERS FERRY
GRAVES MTN.
CHEWELA
GISBORNE MTN.
BIG SWEDE
KALISPELL
DESERT MTN.
SPOKANE
LEGEND
SMALL CUMULUS
TOWERING CUMULUS
VIRGA
PRECIPITATION
CUMULUS - TOP OBSCURED
ICE TOP CUMULUS
THUNDERSTORM
EACH CIRCLE : 20 Mi. RADIUS
(MT. WASHBURN And SCOTT MTN. OMITTED FROM THIS MAP)
MT. COEUR d'ALENE
WILLIAMS PK.
DOUBLE ARROW
BALD MTN.
JERRY JOHNSON
MISSOULA
HEMLOCK BUTTE
SLIDEROCK
COOLWATER
WASHINGTON
OREGON
GRANGEVILLE
DEER MTN.
COLD SPRINGS
GREEN MTN.
LAGRANDE
HORSE MTN.
LONG TOM
SALMON
RUSSEL MTN.
NEW MEADOWS
BAKER

Lightning storm paths.--In the past, all the national forests of western Montana and northern Idaho have had severe outbreaks of lightning fires. During the 15-year period from 1931 through 1945 the Clearwater National Forest in northern Idaho was the most critical lightning fire zone; it had an average annual occurrence of 114 fires per million acres. In 1957 a total of only 13 lightning fires occurred on this forest, and only one occurred in the normally critical month of August. The Project Skyfire cloud survey and reports from fire-weather stations show that only four lightning strike periods were reported during August over the entire Clearwater National Forest.

A review of the cloud-to-ground lightning strike data for the 1957 fire season and the averages over the 1955-56-57 seasons shows a concentration of lightning activity in a line from Horse Mountain on the Payette National Forest through Green Mountain on the Nezperce National Forest in northern Idaho and Deer Mountain on the Bitterroot National Forest to Sliderock and Double Arrow on the Lolo National Forest in Montana (figure 6). The Project Skyfire cloud seeding experimental area is slightly to the northwest of this lightning storm path. The rather consistent lightning storm path shown by this analysis may indicate new priority areas for future cloud seeding research.

Lightning storm types.--Given sufficient moisture and instability in the atmosphere, lightning storms can be started by various causes. There are great variations in the characteristics

Figure 6.--Average annual number of lightning strikes for July and August 1954-1957 as reported by Skyfire lookout network.


MONTANA
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SKYFIRE LOOKOUTS
N. BALDY
GRAVES MTN.
CHEWELAH MTN.
GISBORNE MTN.
BIG SWEDE
DESERT MTN.
KALISPELL
SPOKANE
COEUR d'ALENE
IDAHO
WASHINGTON
WILLIAMS PK
BALD MTN.
DOUBLE ARROW
GREAT FALLS
MISSOULA
HELENA
HEMLOCK BUTTE
JERRY JOHNSON
SLIDE ROCK
COOLWATER
DEER MTN.
BUTTE
GREEN MTN.
COLD SPRING
LONG TOM
HORSE MTN.
RUSSEL MTN.
SALMON
MT. WASHBURN
SCOTT MTN.
100
200
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700

of individual storms. However, observations in the northern Rockies indicate that most storms can be classified into one of three broad types: (1) local airmass, (2) frontal, and (3) high-level, fast-moving lightning storms. Within these broad types there are many varying characteristics; and sometimes the mixing of characteristics between types makes the distinction far from clear-cut.

The local airmass lightning storm is the classic type best known to most observers. One common factor present in a majority of typical airmass storms is the additional instability produced by ground surface heating. This storm type grows in the general area where clouds form, moves relatively slowly over widely varying distances, and may last from a few minutes to several hours. During the summer months such storms in the northern Rockies have cloud bases 5,000 to 10,000 feet above the general topography. Precipitation from such storms usually is very light, but heavy showers and some hail may fall in local areas. When cloud bases are very high, virtually no precipitation reaches the ground, but a large number of cloud-to-ground lightning strikes may occur. Because of the convectional activity normally present, this type of storm makes a good target for seeding with ground-based silver iodide generators.

The frontal type lightning storm has some characteristics similar to those of the airmass type. Orographic lifting of air is often associated with both types, and the amount of moisture

in the lower layers of the atmosphere is an important factor. In the frontal storm, additional instability is furnished through lifting of the lower layers with the movement of the colder air. Frontal type storms generally move faster than airmass type storms, and vary widely in amount of precipitation they produce. The number of cloud-to-ground lightning strikes also varies widely. Most of the 1,100 lightning fires that occurred in the northern Rockies during August, 1953 were produced by frontal type storms. Because of the orographic lifting involved, this type of storm should be a possible target for seeding from properly located ground-based generators.

The high-level, fast-moving type of lightning storm has characteristics different from those of the other two broad types. One important weather influence is the presence of a cold low pressure area at high levels off of the northwestern Pacific coast. The development or deepening of this low brings cold air in over the northern Rockies in the upper levels, and thereby increases the instability through the colder temperatures aloft. In this type of storm the concentration of moisture in the higher levels is very important.

When the cold low pressure center or trough moves across the northern Rockies, lightning storms may result from convergence in the higher levels. Often only a minor wave moves across the area but it may produce similar results. These waves are very difficult to detect, follow, and forecast. These storms move rapidly, have very high cloud bases, and produce little precipitation

that reaches the ground. Surface heating and convective currents from the ground play only a minor part in these storms. In some situations the storms may develop from the alto-cumulus cloud layer.

VI. PRELIMINARY CLOUD SEEDING RESEARCH

Cloud Seeding Experiments in Arizona 1956

In the spring of 1956 Project Skyfire carried on exploratory cloud seeding research in the San Francisco Peaks area of the Coconino National Forest in northern Arizona. The purpose of this operation was to try out cloud seeding techniques on growing cumulus clouds, investigate methods for physical analysis of cloud seeding results, and test several items of equipment required in this type of research.

The Southwest is a good region for experiments in the seeding of cumulus clouds. Relatively simple, orographic airmass type lightning storms occur frequently in this area during the late spring and early summer. The Coconino National Forest has an annual average of 366 lightning fires.

The Arizona experiments provided the first trial by the Project Skyfire staff of a system of coordinated aerial and ground observations during the seeding of cumulus clouds. Measurements and observations were made from two ground stations and two aircraft. A radio network connected all observers and provided a means for continuous coordination of operations. The Skyfire mobile radar unit was used for the first time in storm observations. Cloud seeding was performed with both airborne and ground-based silver iodide generators. The plume from the generators was sampled through the use of a portable cold box in an aircraft. Measurements were made of condensation and freezing nuclei at ground levels and up to 20,000 feet.

The principal accomplishments of the Arizona experiments were the testing of special cloud seeding techniques and equipment. During much of the operation cloud conditions were not favorable for extensive seeding. However, some cloud modification was evident on days when satisfactory cloud situations developed. Seeding from an aircraft flying below the cloud bases indicated modification such as the formation of virga, changes in height and structure of cloud bases, and glaciation in the upper portion of the clouds. In some cases radar echoes were picked up in seeded clouds. The overall results showed the possibilities for physical analysis of cloud seeding results through a coordinated program using aircraft, radar, cloud photography, nuclei measurement, and weather analysis. (15).

Cloud Seeding Experiments in Northern Rockies, 1958

Immediately following the Arizona experiments a second exploratory cloud seeding operation was started in the northern Rockies. The experimental area was established on the Lolo National Forest near the summit of the Bitterroot Range along the Idaho-Montana border. The purpose of this operation was to continue experiments of cloud seeding techniques, testing of equipment, and study methods for physical analysis. Coordinated aerial and ground observations, tracking of storms by radar, nuclei sampling, cloud photography, and weather analysis were employed in the operation. Three types of cloud seeding were tested: ground-based silver iodide generators; airborne silver iodide generator; and dry ice seeding from aircraft. (16).

Silver iodide seeding from ground-based generators.--During the late summer of 1956 four string-burning and ten acetone type generators were tested in the Lolo National Forest experimental area. Local effects on clouds were observed including virga formation, some precipitation, and glaciation. However large scale transformation of supercooled water droplets to ice crystals was not observed. These experiments demonstrated the need for a high output generator designed for long periods of economical operation in remote mountain country. Use of the available generators permitted testing of techniques for silver iodide plume tracing and determination of concentrations at various flight levels. Also the experiments yielded information on the placement of generators in relation to topography and observation sites in this area. Each of these findings from the ground-based generator experiments proved especially valuable in the design of later research operations.

Silver iodide seeding from aircraft.--The airborne generator is a type in which a battery operated motor feeds silver iodide impregnated cord into an oxy-propane flame. The generator is mounted in a Cessna 180 aircraft. A flexible pipe extending from the generator to a venturi tube below the fuselage carries the silver iodide crystals to the outside air. (See figure 7). Calibration of this generator shows a production rate of about 10^{13} crystals per second effective near -20°C. This production rate is satisfactory for small scale cloud seeding experiments.

Figure 7.--Airborne cloud seeding generator mounted in Forest Service Cessna 180 aircraft. This generator burns sash cord impregnated with silver iodide in an oxy-propane flame to produce the silver iodide nuclei.

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Two general techniques were tested for airborne seeding with silver iodide. A glider type soaring approach was found best for seeding relatively isolated and slow-moving cumulus. The light plane, at reduced power settings, would soar in tight circles in the region of maximum updrafts and just below cloud base. The technique for long lines of clouds or cloud "streets" was to fly a series of traverses across the wind and below the clouds. A base line was established normal to the cloud movement and some miles upwind from the primary observing area. The plane then began seeding continuously, crossing and recrossing the cloud paths at cloud base altitude over the same geographical line.

The soaring technique of aircraft seeding usually produced the following results: updrafts of 800 to 1,200 feet per minute often were present before seeding began; ten to twenty minutes after seeding began, updrafts ceased and in some cases downdrafts were recorded; virga began falling from the seeded cloud; and ground observers reported glaciation in the upper portion of the cloud. In many cases the cloud started growing again sometime after seeding was stopped.

In traverse type aircraft seeding the same effects were noted as those reported for the soaring technique, but a line of cloud cells for some distance downwind would be in varying stages of the cycle. The most noticeable effects were recorded on August 30, 1956 when a line of intense showers and an extended area of clouds composed of ice crystals developed for many miles downwind from the seeded area.

Aircraft seeding with dry ice.--In this type of seeding dry ice pellets are released from the aircraft into a growing cumulus cloud tower. The flight pattern attempts to cross just above the growing tower with the dry ice released at different rates. Often cloud development would be so advanced that the light aircraft could not get on top of the cumulus towers. In this case the aircraft would cut through one edge of the cumulus and release the dry ice.

The aircraft seeding operations with dry ice were far more localized than other types of seeding. This made observing and recording much easier. In almost every instance in which supercooled clouds were seeded with dry ice, rapid and pronounced action in the clouds was observed. Within five to ten minutes after the dry ice was dropped the seeded area turned to ice crystals and ice crystal virga began falling from the cloud. In most cases this procedure resulted in a complete breakdown of the seeded cloud area.

An example of the results of aircraft seeding with dry ice is the mission of August 8, 1956 carried out over the Lolo National Forest. A cumulus cloud with a top of 15,300 feet, temperature at that level -7°C, was seeded with six quarts of dry ice. Cloud thickness was 4,000 feet and upcurrents at flight level were light. The results of this operation are shown in figure 8. The glaciation, virga, and dissipation observed in this cloud were not evident in similar clouds in the immediate area.

1. 1329 hours. Time of seeding

2. 1344 hours (Seed plus 15 minutes)

3. 1350 hours (Seed plus 21 minutes)

4. 1356 hours (Seed plus 27 minutes)

Figure 8.--Dry ice seeding from over Graves Range, Lolo National Forest, Montana. Picture (1) at time of seeding; (2) virga showing from base; (3) extensive virga behind newly formed cloud in foreground; and (4) ice residue remains.

VII. THE 1957 PROJECT SKYFIRE CLOUD SEEDING EXPERIMENTS

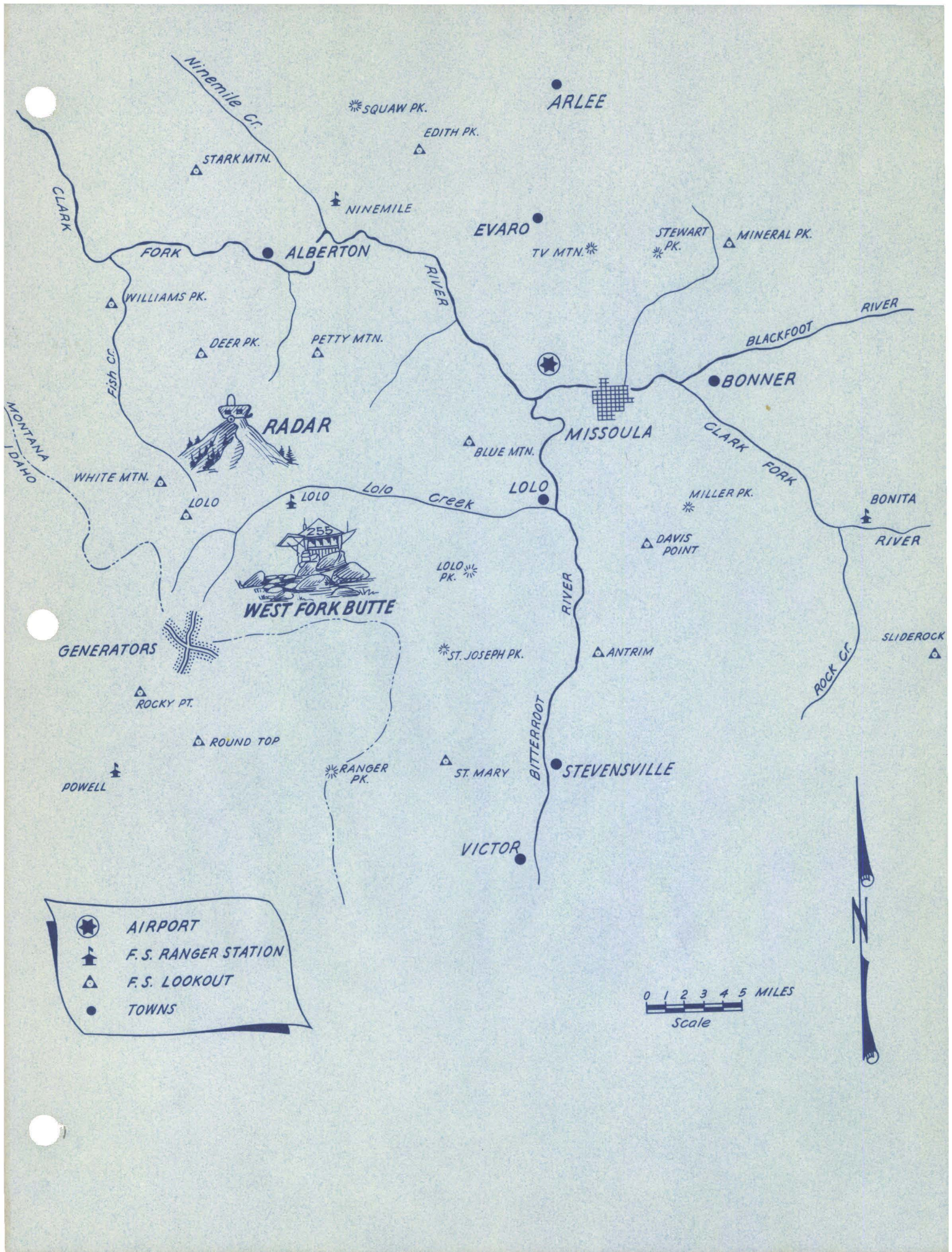
Experiment Objectives and Design

The 1957 experiments were designed to concentrate on observation and analysis of ground generator seeding effects on growing cumulus clouds. The experiment was intended especially to produce large-scale seeding effects within a test area approximately 30 miles in length and 15 miles in width (figure 9). Correlated objectives were to test new cloud seeding generators, study silver iodide nuclei characteristics and concentrations, and continue development of physical analysis techniques.

There are two basic design concepts for this type of research. One is the randromization design wherein the toss of a coin or some other randomization method is used to select periods to seed or not to seed clouds in a field area. Randomization might also be achieved by having two or more test areas which are selected by a similar method. This design has the advantage of permitting systematic statistical analysis. However, it has the disadvantage of restricting the number of seeding tests and requires that some system must be devised to account for the differences in clouds, storms, atmospheric factors, topographic variations, and general weather from one day to the next.

A second basic concept is the comparison design wherein clouds are seeded in a field area at every opportunity and results in the seeded area are compared with adjacent unseeded areas.

Figure 9.--Project Skyfire cloud seeding test area. Major operational points within this 250 square mile area include generator sites, radar installation, West Fork Butte lookout, and airport-Weather Bureau.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WILLIAMS PK.
BLACKFOOT
RIVER
DEER PK.
PETTY MTN.
Fish Cr.
BONNER
MONTANA
IDAHO
RADAR
MISSOULA
CLARK FORK
BLUE MTN.
WHITE MTN.
LOLO
LOLO
Lolo Creek
LOLO
MILLER PK.
BONITA
RIVER
DAVIS POINT
255
LOLO PK.
WEST FORK BUTTE
RIVER
GENERATORS
ST. JOSEPH PK.
ANTRIM
SLIDEROCK
ROCK Cr.
ROCKY PT.
ROUND TOP
BITTERROOT
RANGER PK.
ST. MARY
STEVENSVILLE
POWELL
VICTOR
AIRPORT
F.S. RANGER STATION
F.S. LOOKOUT
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0 1 2 3 4 5 MILES
Scale
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This design has the advantage of permitting the maximum number of seeding tests, but requires the comparison of clouds, storms, atmospheric factors, and general weather between the seeded and unseeded control areas. Wind may change the plume area from day to day. However, it is believed that the comparison between one area and another on the same day can be done with more reliability than comparison of one day with another. For these reasons the design of comparing a seeded area with unseeded areas on the same day was selected for the 1957 Project Skyfire cloud seeding experiments.

In the present stage of the development of cloud seeding knowledge there are many pitfalls in attempts to perform normal statistical experiments to determine possible seeding effects on lightning. The gaining of a better understanding of cloud growth processes and the specific effects of silver iodide nuclei on cloud action is required before the variables of a statistical experiment can be identified properly. Other factors including nuclei generation, transportation and decay, effects of mountain topography on both nuclei and clouds, and influences of large-scale atmospheric patterns also require much additional study. These are basic reasons for the physical analysis type of experiment as carried on by Project Skyfire.

The Test Area

The test area where seeding experiments were conducted during 1956 and 1957 is located southwest of Missoula, Montana on the Lolo National Forest (figure 9). This area is typical

of a large portion of the mountainous terrain in the northern Rocky Mountains and is characterized by heavily wooded slopes, deep valleys, and occasional peaks between 7 and 9 thousand feet in elevation.

A network of ground-based cloud seeding generators was located in the Lolo Pass vicinity along the Bitterroot Mountains on the Montana-Idaho border. This network of generators and the associated test area lies near the center of the Skyfire cloud survey network. Within the test area are two major operational control points: the radar site and West Fork Butte Lookout. These stations are manned by Skyfire staff personnel during seeding operations and provide locations from which observations, photographs, and detailed weather measurements may be collected.

Surrounding the test area is a network of forest fire lookout stations which are conveniently situated for reporting on cloud and lightning activity. Four of these lookouts are members of the cloud survey network and provide detailed cloud and lightning reports daily to the analysis center in Missoula. The other lookouts in the area provide data on time, movement, and intensity of thunderstorms occurring near their stations.

Cloud Seeding Generator Development

Generator studies.--An essential prerequisite for the 1957 experiments was the development of a satisfactory cloud seeding generator. A suitable generator for Skyfire use should have the

following characteristics: production of a relatively high output of silver iodide nuclei; economical and simple operation; easy to transport and service in rough, mountainous country; and be safe for use in highly flammable forests.

Several types of silver iodide smoke generators were field tested by Project Skyfire during the 1956 field season. (6). A program of generator calibration was carried out in the fall and winter of 1956. Eight standard and prototype generators were calibrated for effective output at cold box temperatures from -6°C to -20°C. All generators were compared on the basis of output, consumption rates, efficiency, supply and maintenance problems, and cost (figure 10).

None of the generators tested were found entirely suitable. An acetone burning generator with an internal mixing nozzle produces a relatively high effective nuclei output but is characterized by high consumption rates for solution and propane gas and by irregular operation due to clogging in the spray nozzle. The fact that the acetone solution is under pressure represents a fire hazard. A string type generator, while advantageous from the standpoint of trouble free operation and simple supply requirements, has the serious disadvantage of relatively low output per unit and high initial cost.

Analysis of all available information on generators indicated that not enough was known about the effects of such factors as flame temperature, quench rate, flame chamber shape, injection rate, etc. on the number of effective nuclei produced. A program of

Figure 10.--Skyfire generator and sampling equipment used in calibration studies. An electric fan forces the silver iodide nuclei out of the top of the funnel where sample is taken with a glass syringe. The sample is diluted and introduced into a cold chamber and the nuclei counted.

generator design and calibration investigated these factors (18). The results of these tests were incorporated in the design of the Project Skyfire generator.

Project Skyfire generator.--The Project Skyfire cloud seeding generator is a silver iodide-acetone solution burning unit with an external mixing injection system (figures 11 and 12). The acetone solution is drawn from a reservoir through a modified hypodermic needle and nebulized by a jet of propane gas. The mixture of atomized acetone solution, propane, and air is directed into a flame chamber and ignited. The volatilized silver iodide condenses into crystals as the smoke passes from the flame and around a quench plate mounted above the flame chamber. The silver iodide smoke is carried away from the generator by convective currents and the surface wind. The output of this generator is 3 to 4 x 10^{13} nuclei per second effective at -20°C when consuming 600 milliliters of 4% silver iodide-acetone solution and one pound of propane per hour at sea level pressure (6).

Operational Procedures

The preliminary 1956 experiments started development of operational procedures for the special requirements of Project Skyfire cloud seeding research. Further development of these procedures resulted in a closely coordinated program of aerial and ground observations and a system for measurement and analysis of atmospheric factors, cloud action, and silver iodide nuclei production. The main phases of a typical operation are daily

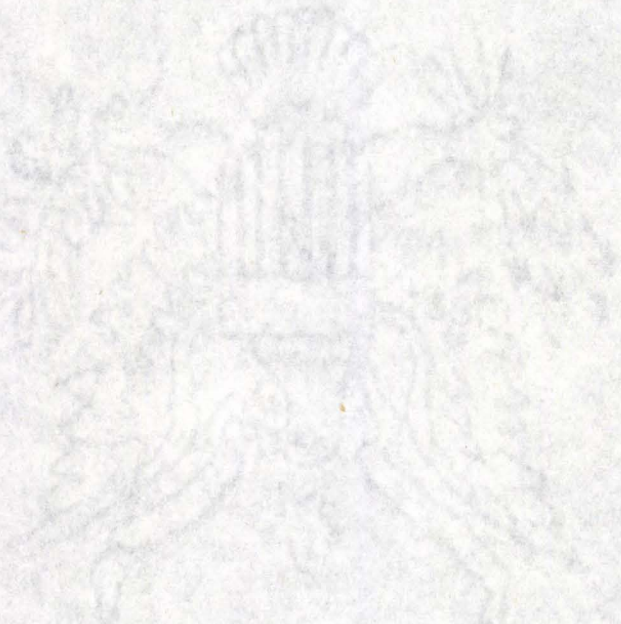

Figure 11.--Project Skyfire cloud seeding generator in operation with windshield being put into position. Propane and acetone-silver iodide solution are burned within the metal flame chamber to produce the seeding material.

Figure 12.--Skyfire cloud seeding generator field installation. Thirty generators were used in the 1957 cloud seeding program. Large openings in heavy timber characterized generator location sites.

briefing and planning session, aircraft flights, radar surveillance of clouds, visual cloud observations, cloud photography, and generator operation. All major activities are coordinated by radio from a central control station.

Daily briefing and planning session.--Each morning during the period of field experiments the Project Skyfire staff meets for a briefing and planning session. Activities of the previous day are reviewed and a weather briefing indicates general possibilities for cloud seeding during the next 24 hours. Based upon the weather forecast specific plans are made for the next operation including aircraft flights, radar activities, cloud observations, and use of cloud seeding generators.

Aircraft operation.--The daily aircraft observations begin with a sounding and reconnaissance flight. The temperature and humidity are recorded on an aerometeorograph. A report on cloud development throughout the region is sent to the weather analysis center. After the morning sounding flight, nuclei sampling flights of several hours duration are made during the day. The background concentration of natural freezing nuclei is measured both in and around the test area. After the seeding generators are in operation, extensive measurement is made of the concentration of silver iodide at cloud base level. The aircraft make observation runs near cumulus clouds in both seeded and unseeded areas and often into the clouds to get such information as the identification

and measurement of hydrometeors, cloud dimensions and growth, path of storms, extent of glaciation, and other measurements.

Radar site.--The radar site serves as a control center for the field activities (figure 13). Hourly surface weather observations and two daily pibal runs are made in addition to the radar operations. Also, the station serves as the communication center for the observation network. The project controller at the site directs the activities of the aircraft in nuclei tracing and cloud reconnaissance. Both time-lapse and still cameras are used to photograph seeded and unseeded clouds.

Cloud observation site.--West Fork Butte Lookout is a surface weather and cloud photography station. In case the view from the radar site is obscured, this station takes control of the aircraft operations. The ten mile separation between the stations makes an ideal base line for triangulation measurements to various clouds and for stereoscopic photography.

Generator site.--A two-man generator servicing crew remains in the Lolo Pass area at all times. The generators can be operated any time a storm is forecast or sighted moving into the area. The generator crew makes surface weather observations, two pibals, and zero-lift balloon runs on all operating days. Radio communication is maintained between the generator crew and the radar control site.

Figure 13.--The Skyfire mobile radar installation on a mountain top in western Montana provides a major control point for directing seeding operation, securing cloud and lightning data, and studying thunderstorm characteristics.

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Weather Analysis

Project Skyfire operations are closely integrated at all times with weather conditions. A preliminary analysis of the previous day's local and large-scale weather patterns is presented at the morning briefing session in order to evaluate the operation. Also, an operational forecast is prepared and issued at this briefing session. This forecast includes: (1) temperature and wind profiles, (2) time of formation and development of clouds, (3) height of the freezing level, (4) height and temperature of the base and top of cumulus clouds, (5) development of thunderstorm activity, (6) turbulence and extent of vertical currents, and (7) location and movement of the jet stream. These analyses and forecasts are prepared from the local project field data and the standard teletype data and facsimile charts available at the Missoula Weather Bureau airport station. Weather conditions are watched during the day for any possible revision of the forecast which would influence the field operations.

The analysis of all cloud seeding results on any given day requires an accurate and detailed background of the weather conditions on that day. These weather analyses are based on the project field weather data, the regular Weather Bureau observations at Missoula and surrounding stations, and the cloud and lightning reports from the Project Skyfire network and other fire-weather stations. Field observations include dry- and wet-bulb

temperatures, and wind directions and speed taken regularly at the generator and radar sites. A special micro-meteorological study is being prepared for the period of July 29-30, when observations were taken for this purpose.

Regular thirty-gram pilot balloon soundings are taken twice daily at both the generator and radar sites. Zero-lift balloon observations are taken at other times as necessary at these sites. These wind reports are used along with the regular Weather Bureau pilot balloon soundings in evaluating the wind field for the layer between the generator level and the cloud base. The observations on cloud modification are analyzed in relation to wind effects on the silver iodide plume at various elevations and on cloud movement.

The necessary teletype data and weather maps (both surface and upper-level) are collected to furnish information on the large-scale weather patterns. These records give information on frontal passages, movement of pressure systems, and jet stream location and movement. Time cross-sections are plotted using the standard level data at all the radiosonde stations in this general area. These cross-sections show the location and intensity of the cold low-pressure system aloft and the eastward and southward displacements of the major and minor troughs across the area. The changes in this cold low system aloft are important factors in the development of thunderstorm activity in this area. These time cross-sections and the plotted radiosonde reports

furnish the necessary information on the moisture and stability patterns.

Records from the Project Skyfire network, the regional fire-weather stations, the Weather Bureau, and C.A.A. stations are used to obtain the distributions of the storms and the number of cloud-to-ground lightning strikes. The normal distribution of the lightning storm days by national forests and the number of cloud-to-ground lightning strikes have been compiled for this area. These normal distributions will be used in the evaluation of the current cloud seeding observations and the planning of future operations.

Each thunderstorm situation is studied to determine the nature of the storm. Whenever possible, the storm is classified in such types as: airmass, frontal, or upper-level.

Use of Radar

During the 1957 operation the radar was located on an isolated peak near the center of the operations area about 20 miles west of Missoula, Montana. Radar surveillance for about 40 miles in all directions is assured from the site. The radar set operates during all field operations when there is a possibility of radar echoes. In addition, the set runs on non-operational days such as during frontal passages to track the paths of storm cells and to gather data on rainfall distribution in the area. During all radar operations a photographic record is kept of all echoes that appear on the radar scope.

The mobile radar consists of an extensively modified 10-centimeter unit mounted in a 14-foot trailer (figure 14). The original surplus military radar was modified to operate in the 2860 megacycle weather radar band. The radar antenna, radome, and transmitter are mounted on a platform near the rear of the trailer. A hoisting motor raises the antenna from the stored position to the operating position above the trailer roof. A slave scope and a special 16-mm time-lapse motion picture camera are mounted in a light-tight housing. The camera, triggered by the antenna rotation, takes a single-frame exposure of the scope on each revolution, or exposures at any desired interval through an electronic camera control box.

Nuclei Studies

The nuclei studies for the field season of 1957 were carried out with 30 ground-based silver iodide generators, two light aircraft, and two portable cold chambers (figure 15). Radio communication between ground observation points and the two aircraft helped coordinate efficient tracing patterns when convective areas could be seen more easily from the surface.

The cold box is mounted in the starboard front seat position of a Forest Service Cessna 180 aircraft (figure 16). The procedure followed by the plume-tracing aircraft in gathering data is: first, to determine a background count for the area by taking samples upwind of the generators and also by traversing the plume beyond its side boundaries; second, to find the upwind

Figure 14.--PPI scope and controls of mobile radar unit used in detecting and tracking thunderstorms in and near the project test area. A special 16 m.m. movie camera photographs a slave scope in a light-tight housing. Camera control box is in upper left.

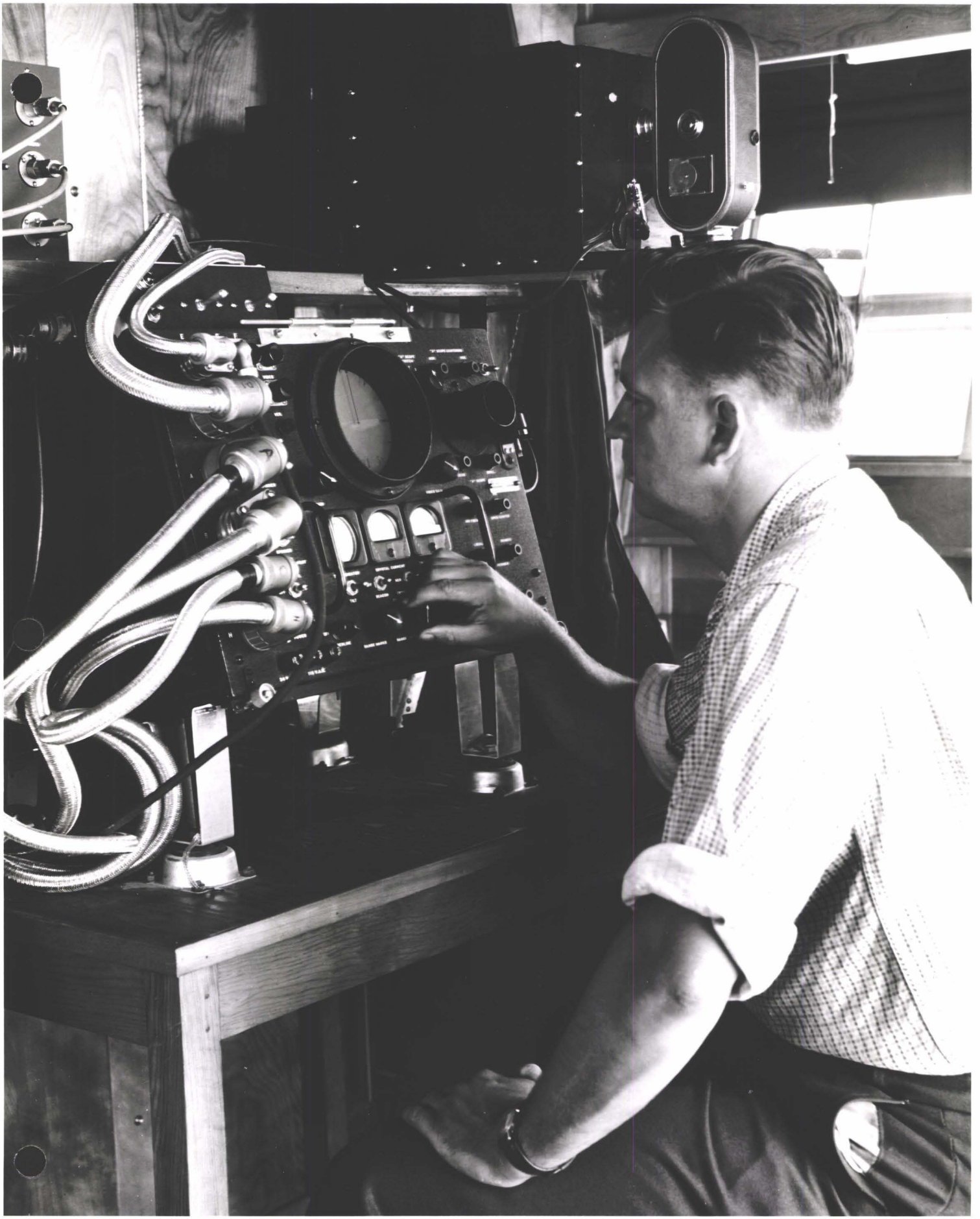

Figure 15.--Adjustments are made on a portable cold box used in detecting the presence of natural and artificial ice nuclei in the atmosphere. The cold box, mounted on the steel framework is positioned securely in the right side of the cockpit after removal of the seat.

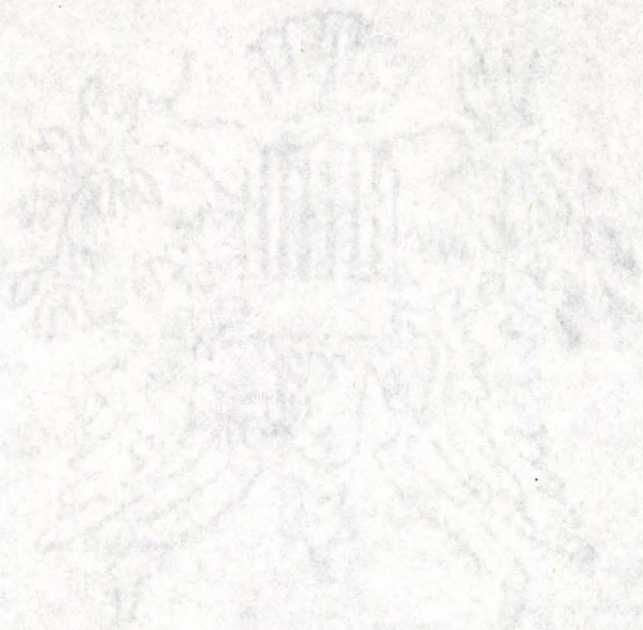

Figure 16.--Portable cold box in position for nuclei flight. The observer sits in the rear seat and looks forward into the cold box when making observations.

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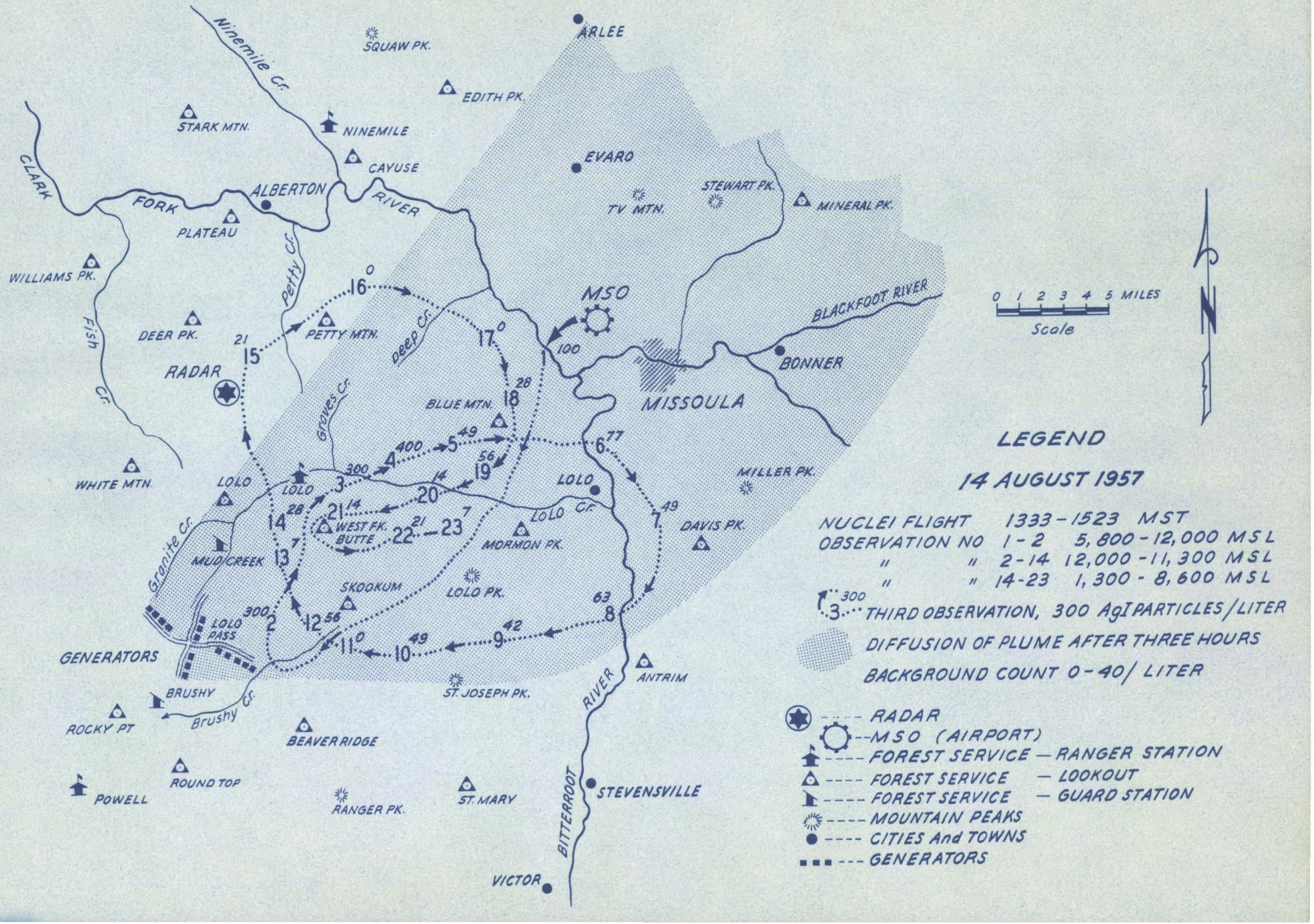
end of the plume by making cold box observations on a series of traverses; and third, to obtain plume concentration and area data by making additional nuclei observations downwind at near constant altitude (figure 17).

Whenever possible a flight pattern is followed which permits sampling under growing cumulus clouds. Vertical currents are estimated from the aircraft's rate-of-climb indicator while flying under constant power settings. This information is recorded in the observer's flight record at each observation time along with the nuclei count, the aircraft altitude, the cold chamber temperature, and location with respect to ground. Nuclei readings are taken every 3 to 5 minutes for 20- or 30-second intervals in relatively low count areas and on a "per view" basis in the higher concentration areas (11).(13).

In the 1957 research program flight times varied from day to day between a maximum of 287 minutes and a minimum of 86 minutes depending upon the ease with which the plume was first located. Average flight time was 182 minutes for the period studied. Wherever possible samples were taken near cloud base, and any cloud under which nuclei were found was examined in detail by both ground and aircraft observers to note any seeding effects.

Figure 17.--A typical nuclei flight map showing sampling point, nuclei concentrations, and flight paths. Nuclei data collected on flights of this nature are used in subsequent analysis to determine the effectiveness of each cloud seeding operation.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DEER PK.
PETTY MTN.
Deep Cr.
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BLUE MTN.
BONNER
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WHITE MTN.
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MILLER PK.
LOLO Cr.
WEST FK. BUTTE
MORMON PK.
DAVIS PK.
Granite Cr.
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SKOOKUM
LOLO PK.
LOLO PASS
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ANTRIM
ROCKY PT
BEAVER RIDGE
ROUND TOP
POWELL
RANGER PK.
ST. MARY
BITTERROOT RIVER
STEVENSVILLE
VICTOR
0 1 2 3 4 5 MILES
Scale
N
LEGEND
14 AUGUST 1957
NUCLEI FLIGHT 1333 - 1523 MST
OBSERVATION NO 1 - 2 5,800 - 12,000 MSL
" " 2 - 14 12,000 - 11,300 MSL
" " 14 - 23 1,300 - 8,600 MSL
300
3 THIRD OBSERVATION, 300 AgI PARTICLES/LITER
DIFFUSION OF PLUME AFTER THREE HOURS
BACKGROUND COUNT 0 - 40/ LITER
RADAR
MSO (AIRPORT)
FOREST SERVICE — RANGER STATION
FOREST SERVICE — LOOKOUT
FOREST SERVICE — GUARD STATION
MOUNTAIN PEAKS
CITIES And TOWNS
GENERATORS

Special Studies

Exploratory studies were carried on of atmospheric micro-pressure changes, atmospheric electricity, and particle size of hydrometeors within growing cumulus clouds. Microbarographs were installed at six stations in the observing network to study pressure changes in relation to thunderstorm movement. Some atmospheric electricity measurements were made at the radar site and the Missoula Weather Bureau station. A particle size sampling device was constructed and used in the aircraft during some of the nuclei sampling flights.

VIII. SUMMARY OF PROJECT SKYFIRE CLOUD SEEDING RESEARCH

General Results of 1957 Experiments

Experimental cloud seeding operations were performed on 29 days during the 1957 fire season in the Lolo National Forest test area. A summary of the cloud seeding program is shown in table 3. Ground-based silver iodide generators were used in all of these tests. The general results show modification of the clouds in the plume area including: (1) partial or complete glaciation in the clouds; (2) changes in structure and growth rate of cumulus clouds; (3) appearance of virga; (4) occurrence of precipitation; and (5) in isolated instances, the occurrence of lightning.

All of the above cloud seeding effects were not present during each operation. The observed modifications are being subjected to analysis in an attempt to explain all seeding effects documented by photographs and measurements from aircraft and ground stations. The preliminary results, based upon the analysis completed to date, are reported here. Later, when all phases of the analysis work are accomplished, a complete technical report will be prepared on the 1957 cloud seeding results.

Seeding Effects

Glaciation.--Observations in the silver iodide plume area show that some degree of glaciation occurred on 24 of the 29 days when ground-based generators were operated. With two exceptions glaciation was observed in all cases where cloud temperatures were

Table 3.--Summary of Project Skyfire 1957 seeding operations

Date	Generators No.	Generators Tot. hrs.	Plume tracing flights No.	Plume tracing flights Time (minutes)	General weather	Freezing level	Cloud data Base Height* ft.	Cloud data Base Temp. °C	Cloud data Top Height* ft.	Cloud data Top Temp. °C	Glaciation in clouds in plume area
July											
8	6	19	0	0	Cb distant SE and S	12,000	E11,000	+2°	14,000	-4°	Fair
9	1	4	0	0	Few cumulus	12,000	E12,000	0°	--	--	None
11	29	178	1	48	Cb distant SE	13,000	11,000	+6°	--	--	None
12	8	53	1	86	Thunderstorm moved across area in afternoon	13,000	15,700	-6°	E25,000	E-25°	Good
15	9	27	0	0	Thunderstorm early a.m. clearing by p.m.	11,000	10,000	+3°	13,000	-6°	Fair
16	13	84	0	0	Thunderstorm and RW in plume area during seeding	11,000	11,700	-2°	19,000	E-20°	Good
17	30	188	1	112	Cumulus clouds	9,000	10,000	-2°	13,000	-8°	Good
19	29	250	1	78	Cb distant morning and afternoon	12,500	10,000	+5°	15,300	-4°	Fair
22	22	134	1	69	RW and thunderstorms during afternoon	12,500	12,500	0°	--	--	Fair
23	26	150	2	149	RW and thunderstorm, a.m. - clearing by p.m.	12,500	9,400	+4°	12,000	1°	None
25	11	27	1	113	Distant thunderstorm, Cb and RW spreading over area	13,500	14,500	-2°	E32,000	E-40°	Fair
26	14	114	0	0	RW-, Cb east and south, spreading over area	12,500	11,500	+1°	--	--	Fair
29	30	156	1	79	Thunderstorm moved across area in p.m.	13,000	11,500	+4.5°	E25,000	E-27°	Good
30	16	54	1	144	Cb distant east and south	12,500	13,000	-1°	16,500	-7.5°	Fair
Aug.											
5	7	15	1	139	Cb distant east	13,000	11,300	+4°	13,500	-1°	None
6	10	44	0	0	Thunderstorm a.m., few RW- late p.m.	10,000	9,000	+2°	14,000	-8°	Good
7	8	23	2	237	Cumulus clouds	10,000	10,000	0°	15,000	-9.5°	Good
8	16	56	3	330	Cumulus clouds	12,000	12,000	0°	14,500	-4°	Fair
9	16	56	1	121	Distant thunderstorms to E late evening	12,600	15,000	-7°	E18,000	E-12°	Fair
14	15	98	1	110	Cumulus clouds	11,000	13,800	-8°	E16,500	E-13°	Fair
15	13	91	1	80	Cumulus clouds	11,700	13,500	-4°	E17,000	E-11°	Fair
16	4	32	1	80	Cb distant SE afternoon	12,000	13,600	-3.5°	17,000	-9°	Good
19	27	104	3	336	Lightning strike in plume area	12,200	12,200	0°	20,500	-17°	Good
20	6	36	1	86	Cumulus clouds	12,000	15,000	-8°	17,000	E-12°	Fair
21	15	42	2	183	Distant thunderstorm late evening	11,900	12,900	-3°	E14,900	E-7°	Good
22	30	278	3	432	Thunderstorm early a.m., clearing by p.m., distant Cb afternoon and evening	10,500	11,600	-2°	E25,000	E-25°	Good
23	15	81	1	90	Distant RW	11,900	14,000	- 6°	E20,000	E-17°	Fair
27	15	86	1	71	Light RW- during p.m.	7,800	8,300	0°	--	--	Obscured
28	15	84	1	79	Cb in distance - moved across area in p.m.	9,000	10,000	-2°	E20,000	E-20°	Fair

RW -- rain showers
Cb -- cumulo-nimbus
E -- estimated
* -- mean sea level

-4° or colder. The two exceptions were July 9 when only one generator was operated and August 27 when low hanging clouds prevented either ground or aircraft observations of the seeded area.

On 10 days during the test period extensive glaciation of the seeded clouds was observed. On each of these days cloud temperatures were -7°C or colder. However, as shown in table 3, temperatures of -7°C or colder do not mean that extensive glaciation will always occur. Other factors, such as moisture content and wind effects on cloud development and the silver iodide plume, will influence the extent of glaciation and hence the degree of cloud modification.

Glaciation was not observed when measured temperatures were warmer than -4°C (table 3). Examples of days with no glaciation were July 11 and 23 and August 5 when temperatures ranged from +6°C at cloud base to -1°C at cloud top.

Silver iodide has been observed causing extensive glaciation in growing cumulus clouds up to 35 miles from the generator site. Glaciation resulting from cloud seeding was photographed extending more than 60 miles from the generator site. This was the extreme limit of the observing network on that occasion.

One conclusion from Project Skyfire operations is that glaciation of both small and towering cumulus clouds invariably results from silver iodide crystal seeding whenever clouds are colder than -4°C and the conditions are such that the silver iodide crystals are carried into the cloud. Therefore, when glaciation

is observed as unique to the small test area and does not appear elsewhere in the observational network, this glaciation is an indicator of the degree of seeding in a cloud system.

Small cumulus clouds.--In small cumulus clouds with the tops at or near the silver iodide threshold temperature (-4°C) the first observable seeding effect was a soft-textured halo around the upper portions of the cloud on the downwind side. The halo appearance was caused by ice crystals, or glaciation, remaining after the water droplets had evaporated on the downwind edge of the cloud.

A more striking effect occurred in small clouds completely cooled below -5°C but still fed by weak upcurrents. The soft-textured halo appeared on the downwind side followed by ice virga. The cloud dissipated rapidly, appearing to be eaten away from below. On the larger clouds of this type an ice residue remained visible for 10 to 30 minutes.

Towering cumulus.--Isolated towering cumulus clouds with the upper portions supercooled below -4°C present a slightly different effect when seeded. A mixture of ice and water particles were present from the -4°C level to about the -8°C level. All of the cloud above the -8° to -10°C isotherm became extensively glaciated. The top turned completely to ice and a long ice streamer often was present extending downwind. The cell growth usually stopped if the cloud was completely glaciated above the -4°C level. Virga or precipitation sometimes were present.

If no virga or precipitation were present, a marked change occurred in the cloud base. Since the cloud had stopped growing at base level, the water droplets in the base evaporated leaving ice crystals in the colder regions. This caused an apparent lifting of the base of two to three thousand feet. The remaining ice cloud, still of towering cumulus dimensions, slowly disappeared by erosion from below, and eventually left a thick alto-stratus layer for one to several hours after the cumulus had lost its identity.

Rapid conversion of the cloud to ice crystals occurred when the entire towering cumulus was supercooled below -4°C. When silver iodide entered this type of growing cloud glaciation began at the base and extended rapidly up through the cloud. When the section of the cloud immediately above the base was glaciated completely before the silver iodide reached the top, the entire cell growth was arrested and the lack of updrafts prevented a high concentration of nuclei from reaching the top. In other cases the cloud glaciated from the base completely to the top. In either instance, the cloud stopped growing throughout all levels and a large ice crystal residue remained long after all visible water had evaporated.

Cloud streets.--Seeding of long cloud streets (10 to 25 miles in length) with a major portion of each cell supercooled below -4°C presented some striking effects. Prior to seeding, the cumulus cells showed normal life cycles of 20 to 40 minutes and maximum growth to the towering stage.

First clear evidence of seeding effects was glaciation on the upper and downwind portions of the seeded tower. This glaciation was clearly visible and remained long after the liquid portion in the same cloud element had evaporated. Ice formation occurred rapidly through all portions of the cloud colder than -4°C, the effect starting from below and working upward through the cloud. The upper one-third of the cloud when completely glaciated would continue to rise and sometimes broke away from the main portion of the cloud. The glaciated section of the cloud drifted downwind as the lower portion collapsed leaving extensive ice residue.

The visual effects from seeding an active cloud street were unique (figure 18). During the initial seeding, the effects previously stated were present. After the cloud street developed and extended into the plume area the following effects took place. All of the cloud above -8°C was glaciated extensively but not sufficiently to arrest growth in the lower portions of the cloud. The upper one-third of the cloud was virtually all ice and showed little growth. This resulted in a continued supply of ice crystals being carried up from the growing portions of the cloud into the more stable top region. A heavy streamer of ice crystals diverged from the cloud top and extended downwind for several miles similar to false cirrus from a thunderstorm. This process continued for several hours and as long as active cells grew in the cloud street. It is significant to note that the cloud street ended at the glaciated cells and no new cells developed downwind within the limit of the observing network.

1. 1655 hours

2.1705 hours

3. 1710 hours

4. 1715 hours

Figure 18.--Clouds southwest of West Fork Butte on August 22, 1957 showing glaciation resulting from seeding operations in the Lolo Pass vicinity. Cloud base 11,600 feet and -2°C; cloud top estimated 17,500 feet; temperature -7°C at 13,200 feet; average wind direction 270° at cloud base. Nuclei counts taken at 8,400 feet under the base of this cloud, and counts taken within 4 miles of the area between 1644 and 1705 hours measured maximum concentrations ranging from 100 to 500 freezing nuclei per liter effective at -20°C.

Photos show: (1) Some glaciation is evident in the left edge of the cloud; active cells may be seen growing on the right, or upwind side; (2) large-scale shifting of water droplets to ice crystals occurred in less than 10 minutes; and (3) and (4) characteristic fanning out and movement of ice shield downwind from the generator area.

Lightning

During July and August of 1957 lightning storms were reported on 27 days by observers in the test area or by one or more of the five Project Skyfire stations in adjacent areas. Cloud seeding operations were performed on 13 of these days (table 4). Lightning occurred in the test area on 4 days prior to the time when generators were turned on. On 3 days storms which developed outside the plume moved into the test area and produced lightning.

Analysis of lightning storm development and movement has not been completed. In addition the few cases now available for analysis may limit the conclusions which can be made on the degree of lightning suppression, if any, from cloud seeding operations. Lightning occurrence from clouds developing in the plume area is of particular importance from the standpoint of the effects of seeding on cloud dynamics and electrification. Two such cases occurred. On July 16 several cloud-to-ground strikes, hail up to 1 centimeter in diameter, and very large raindrops were observed coming from an extensive cloud mass about 30 miles from the generators. Only moderate glaciation was observed in the cloud mass. On August 19 lightning to ground occurred in the plume area from a small cloud less than 6,000 feet thick. The downwind portion of the cloud was seeded and produced graupel and rain. A single weak lightning strike occurred from the upwind, apparently unseeded portion of the cloud immediately after precipitation began falling from the seeded section. This was the only strike occuring this day within the test area.

Table 4.--Summary of lightning occurrence in Project Skyfire test area and adjacent areas on days when cloud seeding generators were operated, July-August, 1957

	Time generators operated	Lightning time in test area	Time of lightning in adjacent areas 1/				
			Jerry Johnson	Williams Peak	Deer Mtn.	Slide-rock	Double Arrow
July							
12	0920-1655	1700-1920			1650-1810	1830-1850 1840-1915 1900-2015	1714-1835 1847-2015
16	0855-1750	1509-1740					1715-2215
19	0745-1838	1605-1606			0145-0300 0520-0745 0945-1030 1715-1804 1845-1935	0300-0325 0700-0820 1110-1130	
22	0850 - 1735	None	1420-1450 1430-1500	1530-2030	1255-1630	1357-1453	1515-1630
23	0835-1645	None					0030-0145
25	1229-1557	1300-1700	1550-1630				1610-1900
26	0729 1635	None			1251-1515 1850-2050		
29	1130 - 1856	1405-1716		2020-2030 2325-2400	1210-1245		0002-0020 0015-0025 1540-1630
Aug.							
5	1155 - 1450	None			1645-1730	1730-1805 1905-1940	1642-1710 2030-2115
6	1054-1605	0120-0724 1630-1700	0200-0330	0130-0500	0020-0210 0200-0335 0345-0820	0415-0440	0245-0330 0415-0430 0505-0525
19	0848-1700	1605-1606			1330-1410		
22	0735 - 1855	0700	0505-0630		0600-0730 0730-0810 2305-2400		
28	0945-1610	None			1535-1630		

1/ Separate times are shown for the beginning and end of each storm.

Life and Concentration of Silver Iodide Nuclei

Project Skyfire studies show a low rate of decay for silver iodide nuclei produced by ground-based generators during mid-summer months. These studies also show that effective concentrations of nuclei can be transported to cloud bases at least 31 miles from the generator site.

Analysis techniques.--Data from six selected days in July and August of 1957 were analyzed for the decay of silver iodide exposed to natural sunlight in the western Montana region. The decay factor "D" is defined as follows:

$$D = \log_{10} \frac{C_t}{C_m}$$

where C_t is the theoretical concentration at a point in the plume and C_m is the measured concentration at the same point.

Results obtained using two different analysis techniques were similar and no significant difference has been found between them.

The first method assumed: (1) a constant generator output of 10^{13} nuclei per second per generator effective at -20°C for all generators in operation regardless of their elevation; (2) homogeneous mixing through all layers from the surface (average elevation 5,000 feet MSL) to cloud base after the first 30 minutes; (3) the boundaries for each half-hour interval projected downwind were determined radially by the wind velocity at selected levels and laterally by plume data. (Where plume data was not available or insufficient a 15-degree half angle pattern was assumed.)

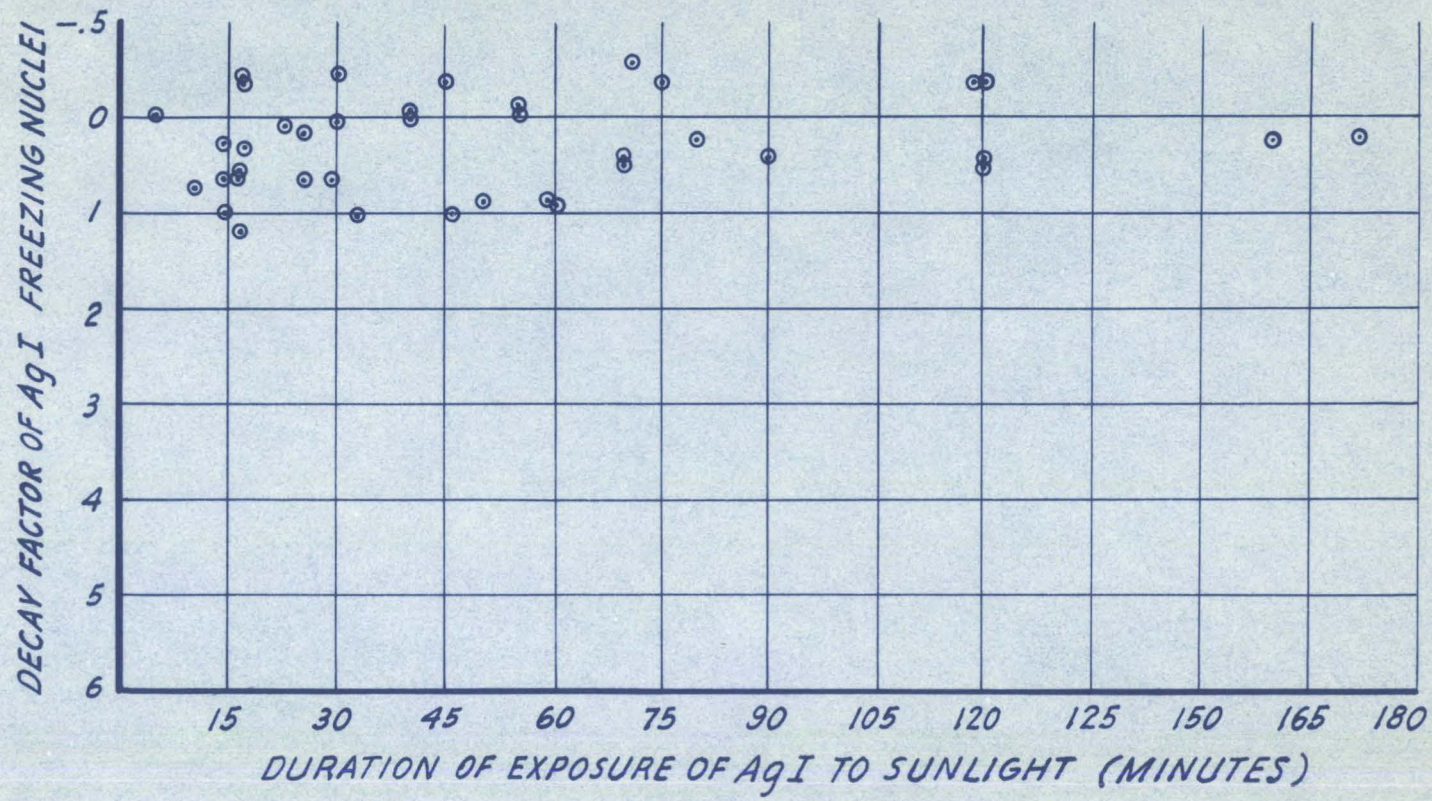
The second method involved calculation of silver iodide decay independent of generator output. The same assumptions were retained for plume boundaries. A measured concentration in the plume was followed downwind to a second measured concentration. The second concentration was assumed to have been decreased from the first by plume divergence and by decay of the silver iodide. The decay between the points was calculated as the ratio of the first concentration decreased by plume divergence to the measured concentration at the second point. An effort was made at all times to minimize the plume volume and thereby increase the maximum possible decay rates computed under the stated assumptions.

Analysis results.--From the 37 observations in figure 19 the following decay information was determined: 75 percent of all observations show a maximum possible decay of less than one order of magnitude per hour; 60 percent show less than one-half order of magnitude per hour. This study shows the decay rate of silver iodide particles in this region is less than one order of magnitude per hour.

Plume areas from the data examined cover an arc of 80 to 90 degrees in five of the six cases studied. This effect was caused mainly by horizontal wind shear in the mixing layers. Most of the plume flights did not cover areas more than 25 miles downwind from the generators because the aircraft was limited in the area it could effectively cover during each flight. The maximum distance the plume was measured from the generators was 31 miles although glaciation was observed downwind for considerably greater distances (60 miles).

Figure 19.--Decay factor of silver iodide versus time for cloud seeding operations on July 12, 23, 30, August 5, 8, and 14, 1957.
Decay factor:

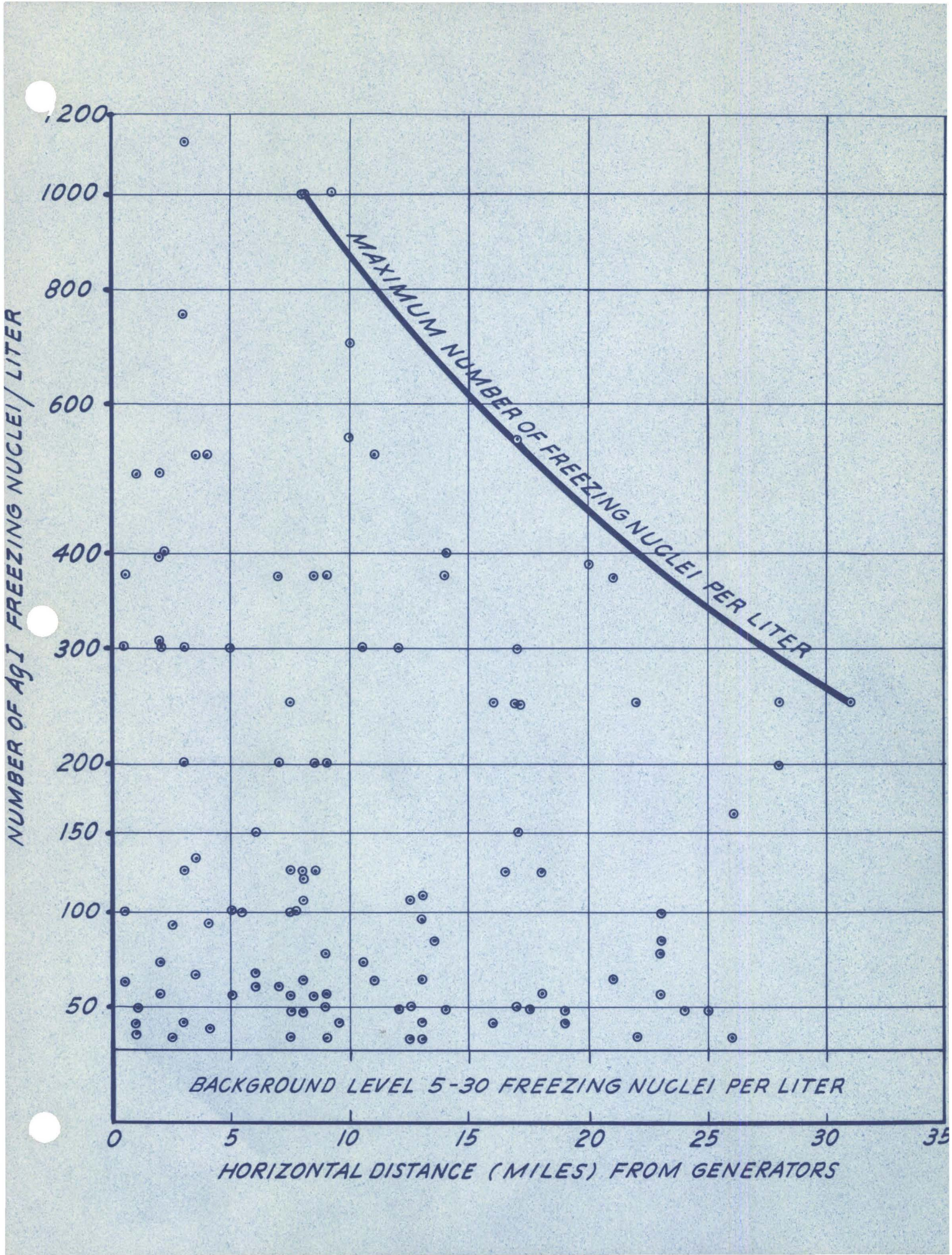
$$D = \log_{10} \frac{C_t}{C_m}$$


DECAY FACTOR OF AgI FREEZING NUCLEI
.5
0
1
2
3
4
5
6
15
30
45
60
75
90
105
120
125
150
165
180
DURATION OF EXPOSURE OF AgI TO SUNLIGHT (MINUTES)

The number of freezing nuclei measured per liter versus horizontal distance from the generators is shown in figure 20. The graph is based on 315 observations on 19 operating days. All nuclei counts were taken at cold chamber temperatures between -19°C and -23°C. The number of nuclei observations was limited to the 25-30 mile range by the 3 to 5 minutes required to take each observation. There are 162 observations not shown on figure 20 in the range 5 per liter to 30 per liter which are background level during the summer months in the western Montana region. Concentrations of 200-300 per liter were measured two hours from the generators at distances up to 31 miles from the source during mid-summer. The average background count of natural freezing nuclei for this region on most operating days was about 10 per liter.

On four occasions generators were operated for periods of four to five hours in the morning prior to the time convection started. On these days ground nuclei runs were made by auto into expected plume drainage areas. The plume was found to drift down these drainages to lower elevations. At the onset of convection nuclei were carried out of the valleys and lifted into cloud bases. This effect was observed to cause glaciation upwind from the generators on several occasions and generally tended to increase greatly the effective area of the plume. Not enough information is available at this time to determine concentrations that might be expected at cloud base from the drainage effect.

Figure 20.--Number of freezing nuclei per liter measured at various distances from generator sites. Data covers nuclei measurements on 19 days.


1,200
1000
800
600
400
300
200
150
100
50
NUMBER OF AgI FREEZING NUCLEI / LITER
MAXIMUM NUMBER OF FREEZING NUCLEI PER LITER
BACKGROUND LEVEL 5-30 FREEZING NUCLEI PER LITER
0
5
10
15
20
25
30
35
HORIZONTAL DISTANCE (MILES) FROM GENERATORS

Tentative Conclusions

1. Glaciation invariably results in both small and towering cumulus clouds whenever the clouds are colder than -4°C and the silver iodide crystals are carried into the cloud.

2. Silver iodide from ground-based generators located in mountainous country can cause extensive modification of growing cumulus clouds at least 35 miles from the generator site during summer months.

3. Extensive glaciation, occurring as a direct result of seeding from ground-based silver iodide generators, can be present at least 60 miles from the generator site.

4. The natural freezing nuclei count in western Montana during the summer months is consistently low. The measured concentration effective at -20°C varied from zero to 30 per liter with an average concentration near 10 per liter for measurements taken from 8,000- to 12,000-foot elevations.

5. The deactivation of silver iodide in the free atmosphere exposed to sunlight is less than one order of magnitude per hour in western Montana during the summer months.

6. A network of ground-based silver iodide generators spaced one-half mile apart in mountainous country can supply sufficient effective nuclei at cloud base to alter decidedly the structure and growth of cumulus clouds at least 35 miles from the generator site.

7. Small growing cumuli, entirely supercooled below -4°C, can be dissipated rapidly by silver iodide from ground-based generators.

8. The growth and structure of towering cumulus clouds with major portions colder than -4°C can be altered by seeding with silver iodide. The growth rate is reduced after most of the supercooled cloud has been converted to ice.

9. A cloud street with cells of towering proportions, mostly in the supercooled state, can be modified extensively by continuously injecting silver iodide into the clouds from ground-based generators. The growth rate of seeded cells is decreased as the upper portions of the cells are converted to ice crystals. The heavy streamers of ice crystals extending downwind from the seeded cells apparently are a factor in inhibiting the growth of new cells further downwind.

IX. RECOMMENDATIONS

Research Program

Progress to date in the development of basic knowledge concerning lightning fires, lightning storms, and cloud seeding has been responsible for providing essential background important to the achievement of new methods in lightning fire suppression. Full realization of Project Skyfire objectives and utilization of the knowledge already gained requires much additional research. The specific types of research needed are as follows:

Basic research of lightning storm electrification to develop a better understanding of the causative factors of cloud-to-ground lightning strikes and variations in lightning storm intensity.

Studies of lightning storm characteristics to obtain additional information on cloud breeding areas, rate of cloud growth, storm paths and variations in storm types in relation to both small- and large-scale weather patterns.

Basic research of freezing nuclei to determine additional information on characteristics of silver iodide and other seeding agents including studies of the effects of particle size, rate of deactivation, and ice crystal formation under various temperature and moisture conditions.

Equipment development including continued work on ground-based and airborne cloud seeding generators, continuous recording and multi-temperature range cold boxes, lightning stroke counters

and recorders, atmospheric electricity recorders, aircraft instruments for measurement of cloud hydrometeors, mobile radar, and special cloud photography equipment.

Field experiments of seeding cumulus clouds to determine specific effects of given amounts of artificial freezing nuclei under various temperature, moisture, wind, and atmospheric stability conditions.

Field experiments on potential lightning storms to obtain quantitative data on the degree of lightning suppression that can be achieved with various techniques of cloud seeding from ground-based and airborne generators.

Lightning storm forecasting research to determine methods for predicting storms in local areas and differences in storm types and intensity.

Research Facilities

Project Skyfire has the advantage of utilizing for research purposes many existing installations required in lightning fire control. These include forest fire lookout stations, communication networks, fire-weather stations, and weather forecasting and analysis centers. In addition, both laboratory and field research facilities should be developed to capitalize fully on the existing resources and to perform the required research program.

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